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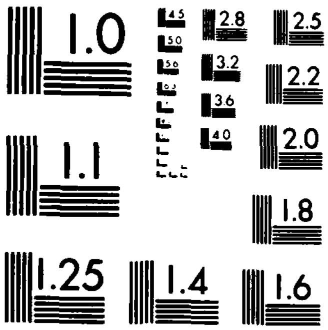

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DESIGN FOR MAINTAINABILITY WITH MODIFIED PETRI NETS (MPNs): SHIPBOARD PROPULSION SYSTEM APPLICATION

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Maintenance of complex systems such as ship propulsion/gas turbine plants poses serious human factors problems for the maintainers. Gas turbine plants typically require a team of maintainers to work with each other on different aspects of a common problem. This paper presents a model-based approach for identifying problem areas resulting from excessive workloads,

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Abstract (cont'd)

and inadequate handling of contingency situations from a maintainability viewpoint. This approach relies on modelling human behavior (i.e., actions, decisions, responses to specific events) within Modified Petri-net representations. It is shown that within this framework, it is possible to (a) identify procedural inconsistencies and ambiguities that may impair human performance; (b) explicitly model contingency handling procedures; (c) compute instantaneous and sustained task-related workload; and (d) develop guidelines for determining where aiding, automation or task reallocation may be warranted. The approach along with illustrative examples is presented within the context of a selected problem area associated with the maintainability of gas turbine propulsion systems.

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ABSTRACT

Maintenance of complex systems such as ship propulsion/gas turbine plants poses serious human factors problems for the maintainers. Gas turbine plants typically require a team of maintainers to work with each other on different aspects of a common problem. This paper presents a model-based approach for identifying problem areas resulting from excessive workloads, and inadequate handling of contingency situations from a maintainability viewpoint. This approach relies on modelling human behavior (i.e., actions, decisions, responses to specific events) within Modified Petri-net representations. It is shown that within this framework, it is possible to (a) identify procedural inconsistencies and ambiguities that may impair human performance; (b) explicitly model contingency handling procedures; (c) compute instantaneous and sustained task-related workload; and (d) develop guidelines for determining where aiding, automation or task reallocation may be warranted. The approach along with illustrative examples is presented within the context of a selected problem area associated with the maintainability of gas turbine propulsion systems.

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1. INTRODUCTION

Propulsion and power plants today often are large and complex. Their control and maintenance involves critical coordination among the operators/maintainers and complex human-plant interaction. These plants (e.g., shipboard propulsion systems, nuclear power plants) are typically maintained by a team of noncollocated maintainers that at all times have to be aware of each other roles and safety requirements. Two main characteristics make propulsion plant maintenance particularly difficult: first, the propulsion plant consists of distributed subsystems; second, maintenance of these systems is largely a decentralized operation. A distributed system is characterized by physical components that are not collocated along the information flow path. In a decentralized operation, local control and decision functions are performed by independent components/operators. In other words, there are multiple loci of decision and control in performing overall system maintenance. In sharp contrast, centralized systems consist of system operation and control processes that share a common, deterministic view of the state of the entire system. In a decentralized system, the various components/operation are, at best, only loosely-coupled. Consequently, human-machine communication and inter-human coordination are subject to both time delays and errors.

Instances of progress in decentralized control systems include advances in automation technology (Avizienis, 1978; Lee, 1981; Perkins and Sargent, 1982) and control theory (Athans, 1978; Roffel and Rijnsdorp, 1982). Yet, surprisingly few studies, relatively speaking, have focused on human supervision, control, and maintenance of these systems. Johannsen (1981) explored the concept of supervisory fault-management aids for decentralized systems. Froquer and Meijer (1980) and Bastl and Felkel (1981) investigated the use of cause-consequence trees for interactive on-line alarm monitoring systems. Sheridan (1981) and Johnson and Rouse (1982) summarized and classified generic human errors in the process plant environment. These and other earlier studies (e.g., Williams, et al., 1982; Report of the President's Commission on the Accident at Three Mile Island, 1979) have shown that there are serious human-related problems associated with the maintenance of decentralized systems (i.e., systems consisting of spatially separated but functionally interconnected elements).

Traditional attempts to evaluate and improve human task performance have focused on centralized systems (e.g., electronics and aircraft) characterized by rapidly changing subsystem states. Consequently, the maintenance of these systems (e.g., electronic systems) has seen significant improvements with the incorporation of automated test equipment and on-line maintainability aids. On the other hand, problems unique to the management and control of decentralized systems, while generally recognized, have yet to be investigated by the research community. Consequently, the lack of progress in maintenance of these systems does not come as a total surprise. Specifically, there are two main causes of this lack of progress that can be readily identified. The first is that maintenance/maintainability aiding technology from centralized systems does not directly lend itself to decentralized systems because the characteristics of the two are quite different. A comparison of power/propulsion plants and electronic system characteristics (see Table 1) readily shows that the operational complexity of the former generally exceeds that of the latter. The second reason is associated with the difficulty in identifying and quantifying maintenance and maintainability related problems arising from poor definition, incomplete/imprecise description, and suboptimal assignment of tasks.

In light of the foregoing, it is our opinion that to improve propulsion plant maintainability it is essential to first recognize the critical differences between power/propulsion (mechanical) systems and electronic/electrical systems (Table 1). We believe that these differences result in distinctively different maintenance practices which in turn give rise to significantly different human-related maintainability problems. It appears from a review of these two classes of systems that the differences are by and large due to the different requirements imposed on the maintainer-equipment interface by the external environment. Table 2 presents a comparison of the characteristics of electronic systems and propulsion plant maintenance operations. These differences, especially as they relate to procedural and team coordination aspects, contribute to the unique human related problems associated with decentralized system maintenance and maintainability.

In so far as the identification and analyses of maintainability problems is concerned, traditional human factors and reliability engineering methods may be used for collecting and correlating human performance data associated with specific tasks. However, it is not unusual to find that both the definition and conduct of task analyses often varies from organization to organization. Further, the various types of task analyses that can be performed are generally specific to the functions analyzed by these methods. Regardless of the specific approach, there are usually four key concerns that complicate task analyses:

(1) Accurately defining each level of the performance hierarchy.
(2) Determining the specific level in the hierarchy at which to collect data (e.g., performance cues, associated training problems, etc.) for performance diagnosis.
(3) Determining the various types of data that should be collected to aid in performance diagnosis.
(4) Interrelating specific communication and coordination requirements and expected behaviors associated with each typical, multi-person task.

TABLE 1

COMPARISON OF ELECTRONIC SYSTEMS AND PROPULSION PLANT CHARACTERISTICS

SYSTEM ATTRIBUTES	ELECTRONIC SYSTEMS	POWER/PROPULSION PLANT
. CONFIGURATION	CENTRALIZED	DECENTRALIZED
. SIZE	SMALL	LARGE
. RELIABILITY	CONSISTENT (UNIFORM)	LESS CONSISTENT (VARIABLE)
. PROCESS COMPLEXITY	LOW	HIGH
. SYSTEM LAG	SHORT	LONG
. PHYSICAL LAW	LINEAR, DECOUPLED	NONLINEAR, COUPLED
. ACCURACY	QUANTITIVE	MORE OR LESS QUALITATIVE
. ENVIRONMENTAL DISTURBANCES	WELL-KNOWN	NOT WELL-KNOWN
. PHYSICAL VARIABLE	SMALL	LARGE
. OBSERVATION OF STATE VARIABLES	DIRECT	INDIRECT

TABLE 2

COMPARISON OF ELECTRONIC SYSTEMS
AND PROPULSION PLANT MAINTENANCE

MAINTENANCE-RELATED ATTRIBUTES	ELECTRONIC SYSTEMS	POWER/PROPULSION PLANT
. PROCEDURE STANDARDIZATION	HIGH	LOW
. OPERATION KNOWLEDGE	LOW	HIGH
. TEAM COORDINATION	RARELY REQUIRED	FREQUENTLY REQUIRED
. PERSONNEL TRAINING	HIGHLY CONSISTENT	LESS RIGOROUS
. HUMAN-EQUIPMENT INTERFACE	HUMAN-ENGINEERED	NOT HUMAN-ENGINEERED
. DIAGNOSTIC FEEDBACK	ATE/BITE AVAILABLE	ATE/BITE NOT AVAILABLE
. SAFETY IMPACTS	LOW	HIGH
. SERVICE COST	LOW	HIGH
. HUMAN ERROR COSTS	LOW	HIGH

In the literature, there are at least six task analysis methods, each based upon a different aspect of the operator and task: (1) mission objectives, (2) behavioral analyses, (3) information processing, (4) decision paradigms, (5) subject matter structures, and (6) vocational schemata. These methods employ one of many formal or informal procedures typically with somewhat different objectives, but usually with approximately identical limitations in terms of their diagnosticity, versatility, and ease of application.

Another analysis method, link analysis (Haygood, et al., 1964; Cullinane, 1977, Bonney, 1977), is a global method that is useful for (a) improving interface design and (b) diagnosing to a limited extent the various causes of inadequate human performance stemming from inadequate interface design. Link analysis consists of documenting each interaction among components (e.g., data entry devices, dials, crew members, etc.) over the scenario time line. Its typical output consists of optimized layouts of panels and configurations of work spaces. The main limitation of link analysis is that since its output is purely a frequency plot, it cannot explicitly represent the operational sequence that led to a specific frequency distribution. Further, link analysis requires observing the performance of a task in an actual work setting or at least having access to the work setting and a procedure manual, neither of which may always be possible. In sum, link analysis is supplementary to task analysis, and can be viewed as one method for using the results of task analysis to specify the plausible sources of man-machine interface problems and possible means for rectifying them.

Graphical Evaluation and Review Technique (GERT) is another class of models that has been used extensively in operator activity analyses. This procedure combines flowgraph theory, moment generating functions and Program Evaluation and Review Technique (PERT) to obtain a solution to stochastic problems in task representation (Pritsker and Happ, 1966). The GERT transaction-flow representation method is a general network-based approach that starts with task-paradigm development to identify the subprocesses and the interactions among them. Abstraction of the process dynamics and interactions then leads the way toward simulation techniques and synthesis of submodels. The basic elements of the GERT networks include logical nodes, probabilistic activity "realization," and activity "transmittance" parameters (Whitehouse, 1973). Efforts have been made by several researchers to combine the network approaches with other disciplines such as control theory (Seifert, 1979; Kraiss, 1981), queueing theory (Pritsker, 1979), and knowledge-based production systems (Doring and Knauper, 1982). The technique is quite general and capable of representing various task situations. The main limitation of the GERT-type network is that since the activity attributes are assigned within each node, it frequently gets involved with complex connections and branching of nodes that introduces rigidity in model structure, constraints on model analyses, and high demands on input data.

In summary, a generic approach for task analysis is required for characterizing and analyzing complex situations involving multiple actors collectively engaged in a cooperative task.

To this end, the purpose of this study is to develop a generic approach for (1) modelling and analyzing multi-person maintenance tasks from the viewpoint of identifying potential human-related maintainability problems, and (2) developing guidelines for alleviating their impact on current systems and circumventing such problems in future systems.

At the heart of our approach is a Modified Petri Net-based characterization of multi-person maintenance task. We use this representational framework in developing task information flow models capable of explicitly characterizing individual activities, events and contingencies resulting from the environment or arising as a result of human error. Subsequent simulation and analysis of this network in terms of identifying possible concurrencies and alternate ways of doing the task allows us to identify procedural inconsistencies, ambiguities, resource conflicts, and operator workload, i.e., all human-related maintainability problems. We attempted to verify some of our findings to the extent possible against historical data bases (e.g., 3M) and via expert elicitation. In the next phase of this study, we intend to collect performance data from simulated exercises at Great Lakes Training Center.

In subsequent sections of this report, we summarize the key elements of our overall approach. In chapter 2 we present the basis of our modelling approach, maintainability-related problem selection and characterization. In chapter 3 we introduce the notion of how the model can be used as a guide to identifying operator workload and explain the approach via an illustrative example. In chapter 4, we present the key elements of the software that we developed in support of our analysis. In chapter 5 we summarize our preliminary findings from analysis of Navy 3M data bases.

2. MODIFIED PETRI NET (MPN)-BASED TASK MODELLING

2.1 Modified Petri Net (MPN) Representation

The analysis of multi-person maintenance tasks is based on a Petri net model-based framework. A Petri net is an abstract, formal model of information flow. The properties, concepts, and techniques of Petri nets are being developed in a search for natural, simple, and powerful methods for describing and analyzing the flow of information and control in systems, particularly systems that may exhibit asynchronous and concurrent activities. The major use of Petri nets has been the modelling of systems of events in which it is possible for some events to occur concurrently, but there are constraints on their occurrence, precedence, and frequency.

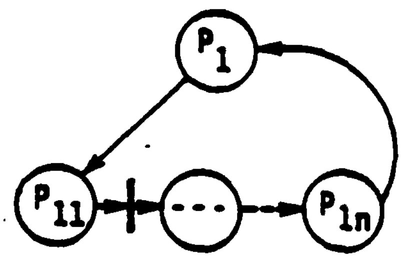
Petri nets have been used in the studies of parallel computation (Miller, 1973), multiprocessing (Agerwala, 1979), computer system modeling (Peterson, 1980), knowledge representation (Zisman, 1978), as well as human processes (Schumacker and Geiser, 1978). The properties along with an example of a Petri net are given in Appendix A.

Petri nets have been adapted and modified in this study in an attempt to overcome either a specific shortcoming or eliminate certain features that can potentially introduce unwarranted complexity in the computer implementation of the net. For the sake of clarity, we will refer to the modified net as modified Petri nets (MPN). The specific constraints and additions that we have introduced in the Petri net are given below, along with a brief discussion of each.

(1) Safeness; Limitations on Number of Tokens. A Petri net is safe if all places in the net are safe. A place in a Petri net is safe if the number of tokens in that place never exceed one. In our implementation we limit the number of tokens in any place to one by disallowing Petri net structures that violate this requirement.

(2) Completion Event. In our interpretation of Petri nets, places are used to represent activities. These activities when completed generate an internal completion event that may be used as one of the requirements for firing a transition and moving the token out of the input place to the output place(s).

(3) Hierarchical Expansion of a Place. A single place in a Petri net can be expanded as a Petri net, starting at a place and ending at a place. This expansion is a deeper level of the net (i.e., a greater degree of detail). Consider place P_1 that is expanded into the subnet P_{11} ..... P_{1n} in the figure below



When a token comes into P_1, a token is immediately placed in P_{11}. The token in P_{11} is then propagated throughout the lower level subnet P_{12} ... P_{1n} until it reaches the "dummy" place P_{1n}. As soon as the token reaches P_{1n}, the internal completion event for the activity in P_1 is set and the token is removed from the "dummy" place P_{1n}.

(4) Aborting an Activity. An output transition associated with a place need not fire after the occurrence of the internal completion event for that place. It can fire "prematurely," that is, before the occurrence of the internal completion event. In this case, an abort is said to have occurred. If the input place is expanded as a subnet, all tokens in that subnet must be removed when the token in the parent place is removed. This process of removing any lower level tokens during an abort involving a hierarchical expansion will be referred to as "vacuuming."

(5) Proper Termination. Petri nets, in general, are not properly terminating. We stipulate that for our MPN to be properly terminating, it must reach a final marking[1], in which only one token remains in the net and that it be in the final place. Thus, a properly terminating MPN guarantees that a final marking will be reached. We impose this restriction on our model for ease of implementation and interpretation.

2.2 Task Performance Interpretation Within MPN Modelling Paradigm

The advantages and disadvantages of Petri Nets, in general, and MPN, in particular, have been discussed at length in the previous sections. In this section, the specifics of MPN in human performance modelling are discussed. The first requirement is to develop a convention for characterizing tasks within an MPN. To this end, the following convention is adopted within the MPN framework.

[1]A marking is the set of all places occupied by tokens at any point in time.

The propositions that are evaluated to determine when a transition should fire are one of the following simple Boolean expressions that is repeatedly evaluated until true:

(1) I

(2) E

(3) $I \wedge E$, $I \wedge E$

When I is not "anded" in an expression in the above propositions as with E or $I \wedge E$, we have a situation where the transition may fire before normal completion of the ongoing activities, producing an abort. Such a transition can be termed a "possible abort transition."

MPN-Based Performance Evaluation

Within the selected event-driven framework several types of performance measures can be defined. In addition to the conventional product measures (i.e., outcome), several process measures can be defined. These include:

(1) Event-related measures.

(a) Correct recognition of an event in terms of correct subsequent action.

(b) Missed detection/recognition of an event (i.e., no action taken when required).

(c) Failure to perform a required activity or subtask in a procedural sequence.

(d) Introduction of an extraneous activity.

(2) Time-based measures.

(a) Time to perform a required activity.
(b) Time to perform a total task.
(c) Time to respond to an action-necessitating event.

The above measures are diagnostic in reconstructing "what went on" in actual task performance. Some of these measures are objective, that is, they can be measured. Others have to be subjectively elicited either post hoc or at suitably selected interim points in actual task performance. In the latter case, the prescriptive Petri net model can be used as a guide to the performance elicitation process.

2.3 Suitability of MPN for Human Behavior/Performance Modelling

Several key features make Petri nets and, in particular, modified Petri nets (MPNs) an appealing framework for modeling multi-person maintenance tasks. Mostly these appealing characteristics arise from the ability of MPNs to represent:

(1) Sequential/parallel processes.
(2) Asynchronous events.
(3) Interactions between concurrent processes.
(4) Temporal order and propagation effects.
(5) Dynamic flow of information.
(6) Varying degrees of detail within a hierarchical structure.

These features can be exploited in human task performance modelling in several ways:

(1) Representation of expert behavior including heuristics and strategies (prescriptive model of task performance).

(2) Representation and monitoring of novice behavior in terms of:

   (a) Competition among actions -- doing one thing inhibits doing another.
   (b) Cooperation among actions -- operations associated with one action are suspended, aborted, or modified to accommodate another.
   (c) Slips of performance -- components of one action sequence are intermixed with components of another. Sequence steps may be omitted, out-of-sync, or inadvertently isolated.

There are several specific potential advantages in employing Petri nets for describing human expert/novice behavior. First, the hierarchical decomposition of tasks into subtasks makes it convenient to focus on human-related problem areas at any appropriate level of abstraction. Second, the token propagation patterns can be used to create procedural templates and loci of potential slips and misses. Third, feedback and coaching can be provided to the operator by insertion of missing elements (e.g., activities, action-related events that were inadvertently left out in the task description and associated procedures). Finally, irrelevant elements can be deleted from task descriptions.

Petri-net representation of multi-person maintenance tasks lends itself to both optimization and revision of maintenance procedures (as originally conceived by the designer or instructor without altering the maintenance task itself). The optimization process consists of first representing the task in MPN formalism and then reducing the net via network manipulation rules subject to system, task and environmental constraints. The reduced net can then be used to write revised specifications for review and revision/certification by the system designer (see Figure 1).

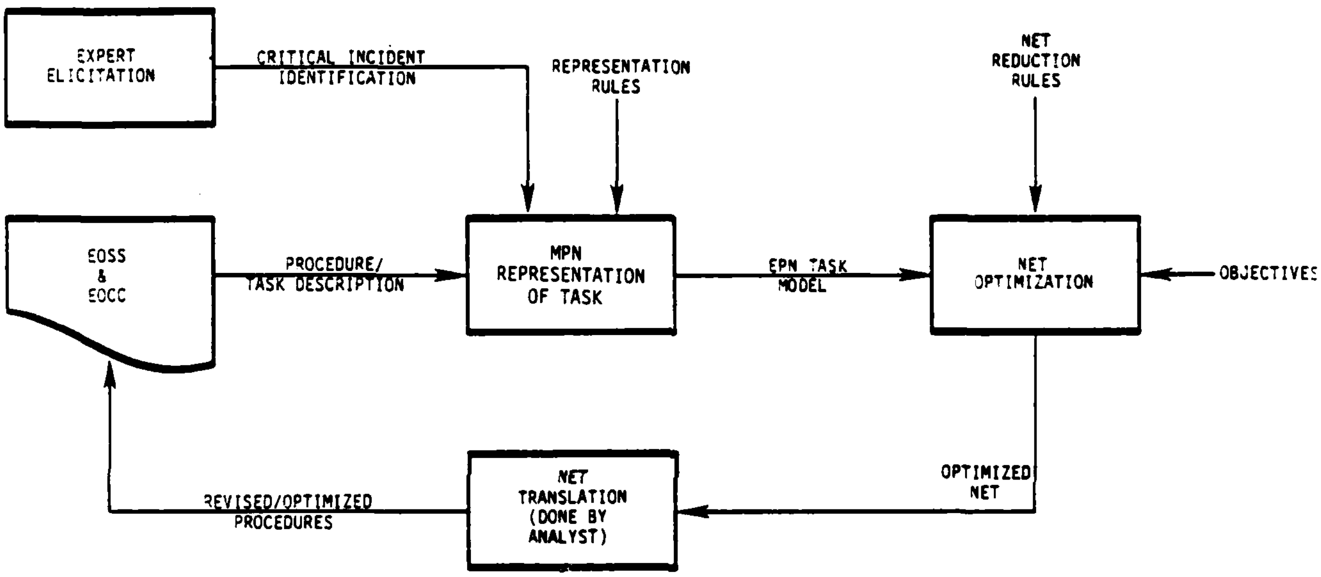


FIGURE 1.
MPN-BASED MAINTENANCE PROCEDURE REVISION/OPTIMIZATION

(1) Places are associated with human-related processes or activities.

(2) Transitions are associated with propositions involving the decision to change from one activity to another.

Places. Human-related processes or activities may be of two kinds: passive (static) or active (dynamic). Passive processes involve wait states, such as monitoring a CRT for a possible error message or waiting for a phone call. Active or dynamic processes involve activities that have a beginning and an end (i.e., completion) such as reporting the position of an oil leak over an intercom.

Transitions. It is worth recalling that within a PN framework, transitions are enabled when all input places have tokens; however, exactly when a transition fires is not defined within the PN formalism. To this end, we can associate the firing of transitions to specific propositions that have to be repeatedly evaluated once all input places to the transition have tokens. This evaluation continues until the transition fires. These propositions are Boolean expressions involving various conjunctive and/or disjunctive combinations of two types of primitives: (a) normal internal completion (I), and (b) external stimulus or condition (E).

(a) Normal Completion Event (I). Normal completion is an internal event associated with the completion of activities associated with all active places input to the transition.

(b) External Event (E). An external event can be: (a) an external stimulus (i.e., a transient or momentary event external to the primary ongoing activities associated with all places input to the transition), (b) a prevailing condition associated with the real world environment or state of the world model at the moment when the real world or its model is "sampled."

The net manipulation rules include:

(1) Eliminating a place (i.e., activity or sub-task) if it does not lead to a subsequent level of performance and/or a maintenance goal.

(2) Combining places (i.e., activities) if two or more places have the same output events. All rules applicable to the original events can then be applied to the new event.

(3) Combining events (i.e., propositions) into a single event (i.e., proposition) if two or more events have the same input and output places.

The MPN model can be used for both descriptive and prescriptive purposes, for behavior and performance measures, to represent both the structure as well as the input-output of task-related activities and processes. The prescriptive MPN can be used to characterize the Engineering Operations Systems Sequence/Emergency Operations Casualty Control (EOSS/EOCC) instructions/procedures. The descriptive MPN, when compared with prescriptive MPN, can provide templates for operator slips and errors. Both behavior and performance can be evaluated within this descriptive MPN. The behavioral aspect of the descriptive MPN models what the operator's action is; whereas, the performance aspect of the MPN models how well the action is performed. Since a model that can accurately predict behavior will also be able to accurately predict performance, but not vice versa, the behavioral model, in general, will be "stronger" than the performance model.

In subsequent sections, a representative propulsion system maintenance task that leads to maintainability-related human factors problems is presented along with a detailed analysis using Modified Petri Net (MPN) models.

2.4 Maintainability Problem Selection

One of the first decisions for this study was to select a high-payoff system and problem area for analysis of human-related maintainability problems. To this end, the following criteria were employed for system and subsystem selection:

(1) The selected system should be characteristic of current and future maintainability requirements.

(2) The selected subsystem should require event-driven responses involving concurrent and coordinated maintainer/operator participation. This includes recognizing combinations of manual/psychomotor, rule-driven/pattern matching and problem-solving behavior on the part of the operator.

(3) System performance should impact platform mission performance.

(4) Operating procedures for the system and subsystems should be sufficiently complex to involve the human performance problems arising from (i) inappropriate task assignments, (ii) task overload/underload, and (iii) inadequate procedural and systems knowledge.

(5) The maintainability procedures associated with the system should be such that a diversity of outcomes (both optimal and suboptimal) can result from them. In addition, procedures should be sufficiently complex to permit operator-induced equipment failure.

(6) The system and subsystems should be amenable to being retrofitted or augmented with total/partial function automation or equipment operator/maintainer aids.

Interviews with supervisory personnel in Navy ships maintenance and evaluation of Navy maintenance requirements and activities related to the selection criteria presented above resulted in one prime candidate system: the LM2500 Propulsion Gas Turbine module as configured for the DD963 class of ship. Specific candidate subsystems included the Gas Turbine Module (GTM) fuel oil system and the lubrication system. The LM2500 GTM system was selected because the LM2500 Propulsion Gas Turbine module (GTM) can be found on three classes of naval combatants: (1) Spruance (DD963) class, (2) Oliver Hazard Perry (FFG 7) class, and (3) Pegasus (PHM1) class.

Future ship classes that will use the GTM for main propulsion are the Ticonderoga (CG 47) class currently authorized for 21 ships through FY 1986 and an undetermined number of undesignated FFX and DDGX vessels. By 1988, it is reasonable to project that of all surface combatants (CG, DDG, DD and FF) 48 percent will be GTM powered and that 92 percent of those that are 15 years old or newer will be GTM powered. Of all GTM powered tonnage, 66 percent will be DD963 power plant configured. In light of the above, the DD963 GTM is preeminently characteristic of both current and future maintainability requirements.

The GTM is the prime power source for propulsion. The DD963 propulsion system requires 4 GTM's. Two GTM's power each of the ship's two propulsion shafts. Failure of a gas turbine and any of its major subsystems results in a direct loss of propulsion horse-power capacity. Supporting the operation of the gas turbine are two major subsystems: the lubrication system and the fuel oil system. Both function continuously during power plant operation.

Consequently, the two subsystems selected for the maintainability study are the fuel oil system and the lube oil system. The fuel oil system is more complicated and contributes to frequent maintenance problems. However, the problems associated with the lube oil system, especially the main reduction gear lube oil system, are time-stressed and can cause greater damage to the gas turbine plant, often leading to total disruption of the ship's propulsion function. Consequently, since the lube oil system poses a more severe maintainability problem to the Navy maintenance personnel, it was selected for an analysis of human-related maintainability problems. A description of the selected maintenance system and tasks is given in Appendix B.

2.5 MPN-Based Characterization of Selected Maintainability Problem

The problem selected for analysis concerns the crew decision-making sequence for the main reduction gear-related lube oil problem. This problem requires coordination, communication, and interdependent decision-making and action taken between the Engineering Officer of the Watch (EOOW) and the engine room operators (EROs). In the following paragrapns the problem-handling sequence will be described in great simplified terms from both the EOOW and ERO perspectives.

The EOOW's Perspective. The EOOW, in the Central Control Station located in the midsection of the ship, is the overall supervisor responsible for monitoring the performance of the propulsion system, supervising and coordinating with the watch team personnel, and making timely and necessary decisions. In this capacity, one of the systems that he is responsible for is the engine room lubrication oil system. (There are two identical systems, one for each engine room.) The information and communication resources available to the EOOW are: instruments that monitor the pressure in the main reduction gear (MRG) and at other strategic points in the propulsion system, sophisticated display systems that provide the operator with status and malfunction information associated with the propulsion system, and various telephones and bi-directional communication facilities for issuing orders and receiving reports.

There are three abnormality conditions that require prompt and sound decisionmaking on the part of the EOOW: report of an engine room fire, a lube oil leak, or a pressure drop on the MRG lube oil pressure gauge. In the following paragraphs, the handling of each of these conditions from the EOOW's perspective are presented along with an explicit characterization of the coordination and communication between the EOOW and the EROs.

For the first condition (i.e., fire reported), the EOOW first acknowledges the receipt of the report using his communication resources and informs the engine room that he is about to recommend for General Quarters (GQ). GQ, a subset of the Emergency Operations and Casualty Control [EOCC] protocol, is a well-documented and rigorously specified emergency control procedure. *The EOOW then hears the engine room operator acknowledge this report, and* indicates his intent to combat the fire. If the fire is serious, then the Officer of the Deck (OOD), the Captain, or Commanding Officer may initiate GQ at his discretion. The full resources of the Engine Room and the EOOW are marshalled to combat the fire. The complex sequence of operations that ensue are oversimplified in what follows. The EOOW proceeds with EOCC procedures while awaiting the next report from the engine room. If the engine room operator reports that the fire is under control, the EOOW may recommend to cancel GQ. If, on the other hand, the engine room operator indicates that the fire is out of control, he also reports that engine room personnel are evacuating, and supplies the names of the evacuating personnel to the best of his knowledge. At this time, the EOOW makes a specific check to ascertain that all personnel that he had sent to the engine room who were not officially on watch have evacuated. The EOOW then verifies that all personnel have indeed evacuated, and proceeds with GQ.

The second contingency condition is the receipt of a lube oil leak report. The report contains both the location and the approximate magnitude of the leak. The EOOW assimilates this information, and evaluates whether the leak is pre-fork or post-fork. (Each engine room has two lube-oil pumps. The oil lines emanating from each pump join together to provide a common feed. A leak before this junction is termed 'pre-fork'; a leak after the junction is 'post-fork'.) If the leak is post-fork, the EOOW apprises the engine room of this fact and initiates EOCC by securing the MRG. If the leak is pre-fork, the EOOW starts the second pump first, then secures the malfunctioning pump, simultaneously informing the engine room of his actions. He then checks the pressure on his gauge and verifies that it has returned to normal. At this point, the EOOW can direct the needed repairs on a non-emergency basis.

The third possible case occurs when the EOOW observes a pressure drop on his own gauge. He verifies the drop through an independent source. This may require the watch stander in the engine room to inspect the gauges on the equipment itself. Conversely, a dedicated display or a plasma display may be used to provide the necessary redundant verification. If the DDI reading is normal, the EOOW calls the engine room and requests confirmation of this fact. When confirmation is received, the EOOW calls another department (GSE) to have the meters checked. If the reading is abnormal, thus verifying the drop, the EOOW informs the engine room of the drop and of the current pressure level. If the engine room indicates that the situation is normal, the EOOW contacts GSE as above. If the engine room confirms that the situation is abnormal, the EOOW orders an investigation and continues to monitor the pressure on his gauge. The EOOW knows that the engine room staff will check the unloader valve first for proper calibration. If the unloader is incorrectly set, the engine room personnel will adjust it. With this adjustment, the EOOW will observe the pressure on his gauge begin to climb. He announces the increasing pressures (feedback) over his communicator, until the pressure reading is normalized.

Adjusting the unloader is a procedure that takes no more than five seconds. If the EOOW does not observe a change in pressure after five seconds he may, at his discretion, send additional personnel to the engine room to help while he awaits the report on the remainder of the investigation. Eventually the EOOW will receive a report on the discovery of a leak along with its location and approximate magnitude. If a leak is reported, the subsequent procedure is identical to that associated with the second condition above (i.e., report on a lube oil leak received by the EOOW). If the report indicates that no leak was found, the EOOW orders the examination of other possible sources of the problem (e.g., meters, pressure sensors, etc.).

In each of the above cases, the final step involves verification of normal operation. When normal operation is verified, the EOOW resumes his watch, monitoring the various gauges on .his control panel. The MPN from the EOOW's perspective is given in Figure 2.

Engine Room Staff Perspective. From the standpoint of the engine room staff, there are, once again, three events that force them to make immediate decisions and take actions: noticing a fire, noticing a lube oil leak, or receiving an order from the EOOW to check out a pressure drop.

If a fire is found, the engine room operator immediately reports it to the EOOW. When the EOOW has responded and informed the engine room that he intends to initiate GQ, the engine room operator acknowledges this decision and informs the EOOW that he will attempt to combat the fire. The engine room staff then employs the fire-fighting Twin Agent System (TAS). (TAS includes Purple K, an agent which reduces the extent of fire so its source

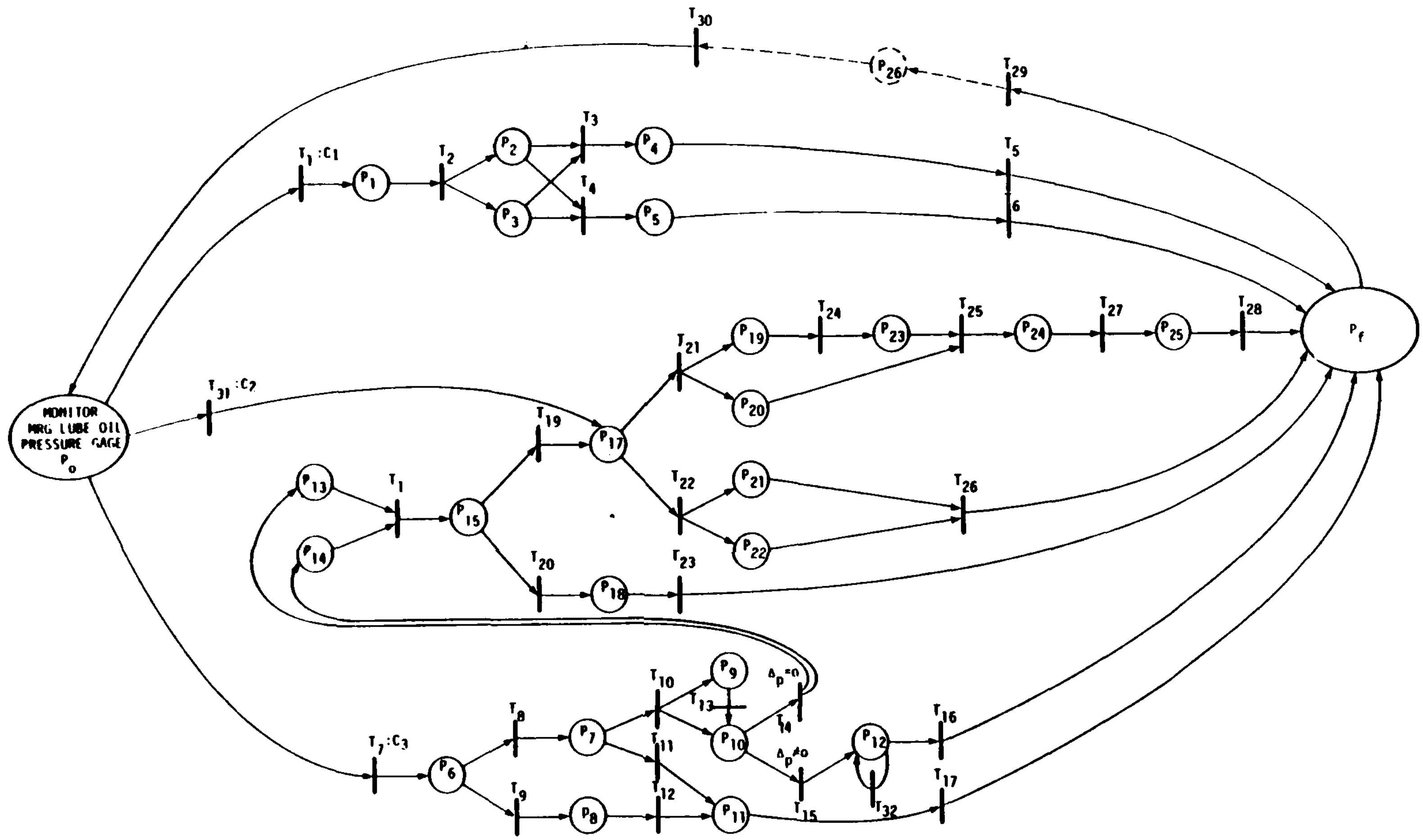


FIGURE 2.
PETRI NETS REPRESENTATION OF EOW REACTION SEQUENCE
TO LUBE OIL PROBLEMS

Places: Definitions

P_0: Monitor MRG Lube Oil Pressure Gage
P_1: Acknowledge Fire Report and Inform Engine Room of Initiation of GQ
P_2: Wait
P_3: Initiate GQ
P_4: Cancel GQ
P_5: Verify Evacuation of Personnel
P_6: Read DDI for Authentication
P_7: Inform Forward Engine Room of Presure Drop (17 psi)
P_8: Call Engineering Officer Present, Request Confirmation
P_9: Order Investigation
P_{10}: Wait and Monitor Pressure
P_{11}: Call up GSE for Meter/Digital Checks
P_{12}: Command Correction
P_{13}: Wait for Report of Investigation
P_{14}: Order Additional Help to Engine Room
P_{15}: Hold
P_{16}: Evaluate Magnitude and Location of Leak
P_{17}: Evaluate/Fix Other Causes (Meters, etc.)
P_{18}: Start New Pump
P_{19}: Inform Forward Engine Room
P_{20}: Inform Forward Engine Room
P_{21}: Secure MRG According to EOCC
P_{22}: Secure Old Pump
P_{23}: Check Pressure
P_{24}: Perform Non-Emergency Repair Procedure
P_{25}: ...
P_f: Evaluate Normal Operation

Transitions: Definitions

T_1: Fire Reported
T_2: Engine Room Reports that Attempt to Combat Fire Will be Made
T_3: Report Fire Under Control
T_4: Report Out-of-Control; Evacuating
T_5: GQ Cancelled
T_6: GQ Initiated
T_7: Pressure Drop Observed
T_8: Drop Authenticated
T_9: DDI Reading Normal
T_{10}: Situation Abnormal
T_{11}: Situation Normal
T_{12}: Confirmation Received
T_{13}: Investigation Ordered
T_{14}: Pressure Drop = 0
T_{15}: Pressure Drop $\neq$ 0
T_{16}: Reading O.K.

T_{17}: Call Made
T_{18}: Report on Existence/Location of Leak Received
T_{19}: Leak
T_{20}: No Leak
T_{21}: Pre-Fork Leak
T_{22}: Post-Fork Leak
T_{23}: Fixed
T_{24}: New Pump Started
T_{25}: Old Pump Secured
T_{26}: Forward Engine Room Informed and MRG Secured According to EOCC
T_{27}: Verify Normal
T_{28}: Non Emergency Repairs Complete
T_{29}: Abnormal
T_{30}: ...
T_{31}: Leak Reported
T_{32}: Continue

can be determined, and AFFF [aqueous film-forming foam], which smothers the reduced fire at its source.) If TAS fails to bring the fire under control, the operator abandons the TAS, heads for the control console, and reports to the EOOW that the fire is out of control and all engine room personnel are in the process of evacuating. He also supplies the names of the evacuating personnel. These individuals then evacuate. If TAS succeeds in bringing the fire under control, the engine room operator reports this to the EOOW.

If a leak is noticed, the engine room operator reports it to the EOOW. Instructions from the EOOW can require the engine room staff to commence EOCC procedures or open and close valves as part of the procedure for switching on one lube oil pump and switching off the other. In the latter case, the engine room operator proceeds to perform the necessary non-emergency repair functions.

In the third case, the EOOW informs the engine room of a drop in observed pressure. The engine room operator checks the pressure and confirms or disconfirms the EOOW's reading. If the pressure is abnormal, the engine room operator is ordered to investigate the cause. The engine room operator firsts check the unloader. If the unloader is poorly aligned, he proceeds to adjust it in response to the changing pressure readings announced by the EOOW. If there is no problem with the unloader, the engine room operator starts to search for a lube oil leak. If a leak is found the engine room operator proceeds as in the preceding paragraph. If no leak is found, the engine room operator reports this to the EOOW. The EOOW then orders an evaluation of other possible sources of the problem (e.g., sensors). Subsequent to traversing any one of these possible paths, the engine room staff is informed when to return to their standby/monitoring watch state. The MPN from the Engine Room Staff perspective is shown in Figure 3.

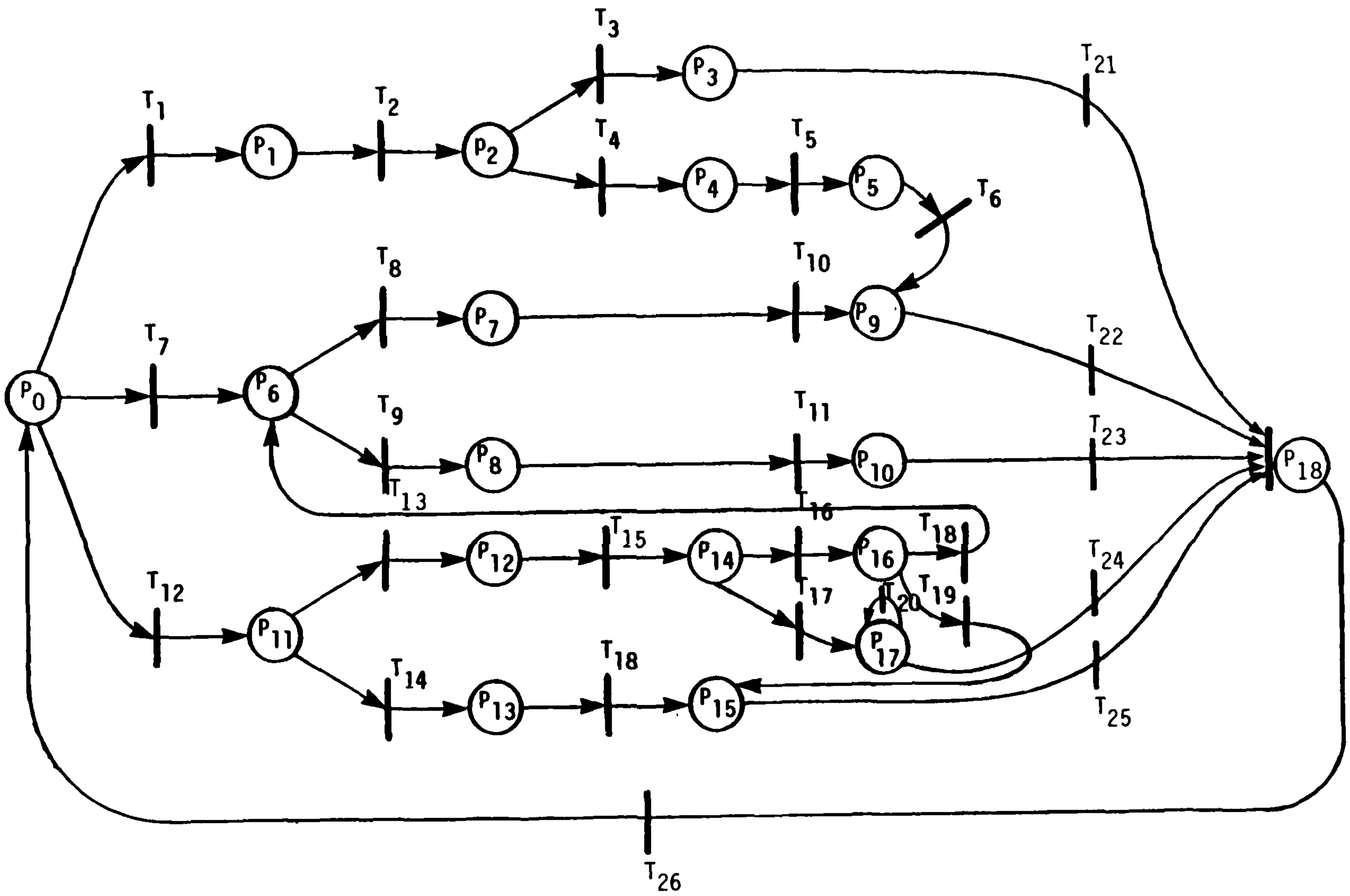


FIGURE 3.
REPRESENTATION OF ENGINE ROOM STAFF REACTION
TO LUBE OIL PROBLEM

Places: Definitions

P_0: Monitor Engine Room and Control Panel
P_1: Report Fire to EOW
P_2: Conduct Fire-Fighting with TAS
P_3: Report Fire Under Control
P_4: Report Fire Out of Control; Evacuating
P_5: Evacuate
P_6: Report Existence, Location, and Magnitude of Leak
P_7: Await Order to Initiate EOCC
P_8: Adjust Valve
P_9: Secure (from EOCC)
P_{10}: Perform Non-Emergency Repairs
P_{11}: Read Pressure Gauge
P_{12}: Report Abnormal
P_{13}: Report Normal
P_{14}: Check Unloader
P_{15}: Check/Fix Other Cases
P_{16}: Check For Leaks
P_{17}: Adjust Unloader
P_{18}: Verify Normal

Transitions: Definitions

T_1: Observe Fire
T_2: EOW Acknowledges, Informs Initiation of GQ
T_3: Fire Under Control
T_4: Fire Not Under Control
T_5: EOW Checks Personnel
T_6: GQ
T_7: Observe Leak
T_8: Post-Fork
T_9: Pre-Fork
T_{10}: EOCC
T_{11}: Normal Operation
T_{12}: Order to Check Pressure Drop Received from EOW
EOW Orders Pressure Drop Check
T_{13}: Pressure Gage Read
T_{14}: Normal
T_{15}: Investigation Order Received from EOW
T_{16}: Normal
T_{17}: Abnormal
T_{18}: Leak Found
T_{19}: No Leak Found
T_{20}: Receive Feedback from EOW

T_{21}: Completion Event
T_{22}: Completion Event
T_{23}: Completion Event
T_{24}: Completion Event
T_{25}: Completion Event
T_{26}: Normal Operation Verified

3. PERFORMANCE AND WORKLOAD ANALYSIS VIA MODIFIED PETRI NETS (MPN)

3.1 MPN-Based Task Performance Elicitation

Given a prescriptive model of actual task performance (i.e., a model constructed with the help of available procedural documentation in conjunction with elicitation from domain experts or "good" performers), it is possible to generate a sequence of questions that are relevant to extracting "unobservable" task performance variables. Specifically, within an MPN framework the types of questions that can be posed to elicit the necessary performance-related information include:

(1) For the problem under consideration what external events require an action response?

   (a) How many such events are there?
   (b) Can any of these occur simultaneously?
   (c) How do you respond to each independently, jointly?

(2) For each antecedent event, how many activities do you perform in parallel?

   (a) Can any of these activities be done sequentially? If so, what are the consequences on overall task performance?

(3) If you are engaged in activity A_1 associated with handling event E_1, and event E_2 occurs which will you choose from the following?

(a) Suspend A_1, respond to E_2 and then resume A_1.
(b) Complete A_1 and then respond to E_2.
(c) Abandon A_1, respond to E_2, continue.
(d) Ignore E_2 altogether.

(4) What is the typical time duration associated with activity A_i?

(5) What are the earliest and latest times for taking action following action-necessitating event E_j?

(a) No sooner than t_{min} after E_j occurs.
(b) No later than t_{max} after E_j occurs.

(6) If there are problems associated with performing activity A_k, then what are the subtasks and events associated with A_k?

3.2 MPN-Based Workload Measures

To estimate/predict upperbound of workload within a modified Petri net (MPN) structure, certain definitions are necessary. The first is the notion of a subnet of a Petri net. For a part of a PN to qualify as a complete subnet of a PN, it must be a connected subnet of a Petri net. With this definition it is clear that a complete subnet is a Petri net and any Petri net is a complete subnet of itself. Since every complete subnet is a PN, it can execute like a PN. The execution of a subnet produces a marking M_t for each time t and a history of "fired" transitions S_i along with their firing times t_i, $(S_i, t_i)_t$ where the transitions are ordered in accord with their firing sequence up to time t. Consider the time t and let the markings M_t have n(t) tokens at places P_i with activity-related loads w_i, i=1,2,... . Also, assume that event-related loads decay exponentially over time. Then, let the cardinality of the set $(S_i, t_i)_t$ be m(t). Let the event load for S_i be v_i. Then the instantaneous workload (t), can be defined as follows.

$$\ell(t) = \sum_{i=1}^{n(t)} w_i + \sum_{i=1}^{m(t)} v_i \, e^{-\chi_i \Delta t_i} , \qquad (1)$$

where $\Delta t_i = (t - t_i)$, and χ_i is a rate of decay parameter for the ith transition. The quantity $\ell(t)$ can be equated to the instantaneous stress associated with the task under consideration.

The cumulative workload up to time t can then be defined as

$$L(t) = \int_{t_0}^{t} \left(\sum_{i=1}^{n(u)} w_i + \sum_{i=1}^{m(u)} v_i e^{-\chi_i \Delta u_i} \right) du \qquad (2)$$

where t has been replaced by the dummy variable u. The quantity L(t) can be loosely equated to task-induced "fatigue", that is, "fatigue" associated with the task under consideration.

Activity Load. The load imposed by an activity is a function of the type of activity (i.e., static or dynamic). The types of activities that the operator engages in can be conveniently classified into skill-based, rule-based and knowledge-based (Rasmussen, 1981). Skill-based activities are primarily psycho-motor or manual in nature (e.g., tracking, manipulating). Rule-based activities are predominantly procedural or pattern-matching. Knowledge-based activities are characterized by a predominant cognitive or problem-solving component. A discussion of each of the above is given in Appendix C. The average load associated with these activities is shown in Table 3.

TABLE 3

AVERAGE ACTIVITY LOAD VERSUS ACTIVITY TYPE

Places (Associated with activities)

Activity Type	Associated Load
Passive	.1
Active	
. Skill-Based	.3
. Rule-Based	.4
. Knowledge-Based	.7

TABLE 4

TRANSITION/EVENT LOAD VERSUS EVENT TYPE AND DECAY TIME

Transitions (Combinations of internal completion and/or external events)

Event Type	Decay Time Constant	Associated Load
. Internal Completion	1 sec	.1
. External		
- expected	2 sec	.2
- unexpected (containable)	4 sec	.4
- unexpected (catastrophic	10 sec	1.0
. Mixed		
(add component weights)	sum	sum

Transition Load. The load imposed by the occurrence of one or more events at a given transition is largely a function of whether the event is internal or external to the task. Figure 4 provides a convenient classification of events for our purposes. Table 4 provides a breakdown of the various event(s) that can occur at a transition, their decay times, and their associated loads.

Path-Related Workload. Within the Petri net framework it is possible to compute several workload measures (see Figure 5). First, multiple path-related workload measures can be computed for each admissible path. Second, both instantaneous and cumulative measures for each path can be computed. In practice, paths are typically designated by the analyst/designer. The PN of Figure 6 will be used as a vehicle to illustrate the notion of a path.

In this example, for instance, the following two major paths can be defined:

$$\text{Path 1: } P_1 \rightarrow T_1 \rightarrow P_2 \rightarrow T3 \searrow P_5 \rightarrow T_6$$

$$\text{Path 1: } P_1 \rightarrow T_2 \begin{array}{l} \nearrow P_3 \rightarrow T_4 \rightarrow P_6 \rightarrow T_7 \\ \searrow P_4 \rightarrow T_5 \rightarrow P_7 \rightarrow T_8 \end{array}$$

From the above, it can be seen that a path is a complete subnet of a PN; it can have both forks (and joins). The underlying idea behind the notion of a path is to identify the worst case workload associated with a task and the designated paths to make meaningful assessments about task reallocation if overall workload is excessive but reallocation is feasible.

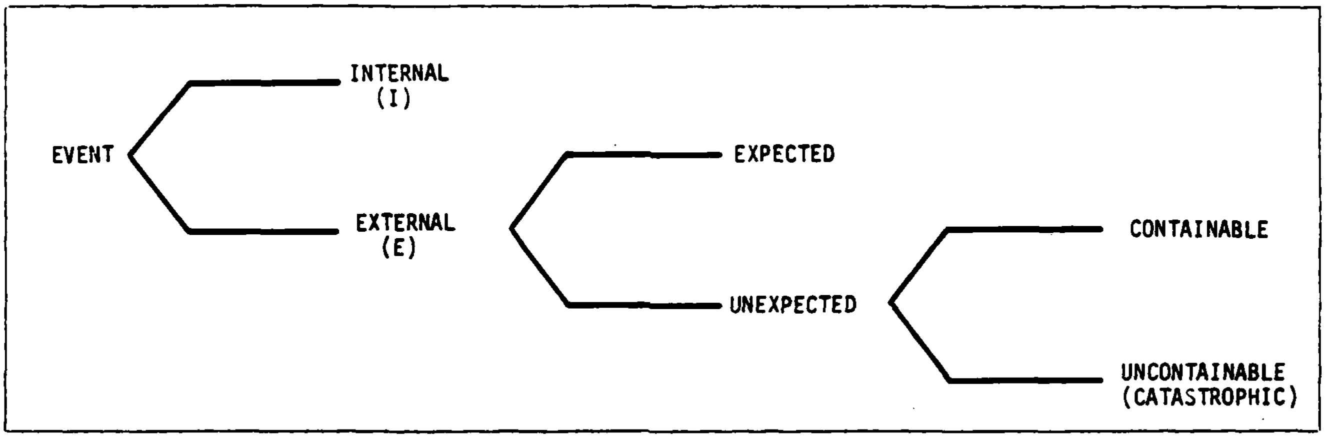


FIGURE 4.
EVENT CLASSIFICATION

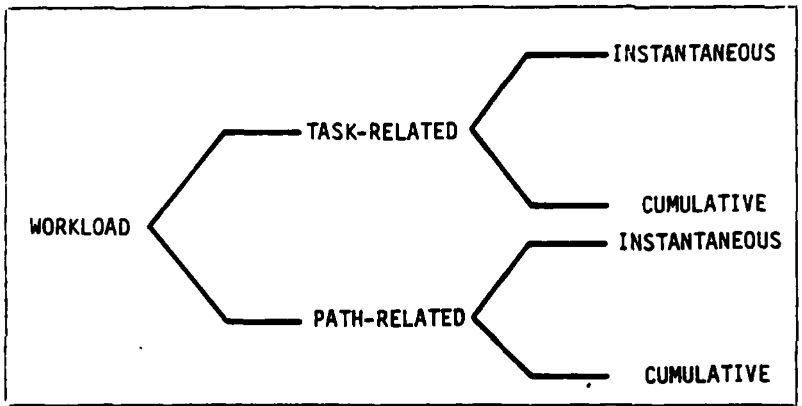


FIGURE 5.
WORKLOAD MEASURES

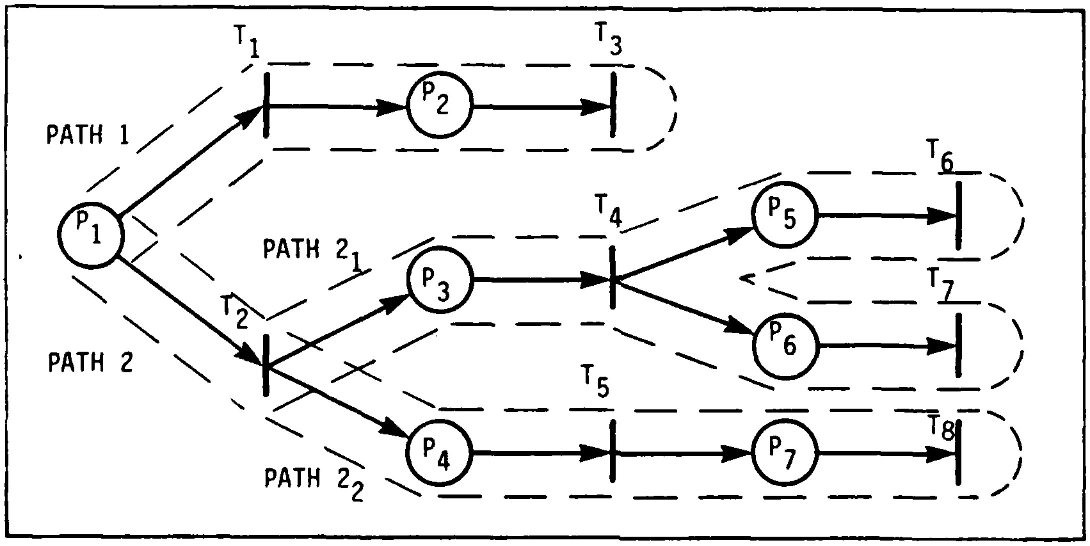


FIGURE 6.
SAMPLE PETRI NET

Thus, we can say that the workload associated with the given complete subnets of Figure 5 is either workload associated with path 1 (WL1) or path 2 (WL2) depending on whether transition T_1 or T_2 fires. Maximum instantaneous workload associated with path 2 (WL2) is the maximum of workload associated with path 2_1 and path 2_2. Maximum overall instantaneous task workload (WL) can then be defined as the maximum of path 1 instantaneous workload and path 2 instantaneous workload.

$$\boxed{\begin{aligned} WL2 &= \max(WL2_1 + WL2_2) \\ WL &= \max\ (WL1, WL2) \end{aligned}}$$

3.3 Illustrative Example

The lube oil problem has been thus far used as a vehicle for demonstrating the representation power of modified Petri net models. In subsequent paragraphs, a key segment of this problem will be abstracted (see Figure 7) and used to illustrate the various workload measures associated with the total subnets and selected paths within it. The illustrative problem is geared to the EOOW's decisionmaking and action sequence. It starts with the receipt of a lube oil leak report from the engine room and ends with the restoration of normal operation. Specifically within this problem representation, the securing of the MRG according to EOCC is expanded in greater detail (Figure 8) to demonstrate the hierarchical modelling aspect of the approach. Subsequently, workload measures (instantaneous, cumulative, and average cumulative) are computed for the total subnet and the designated two paths in the net.

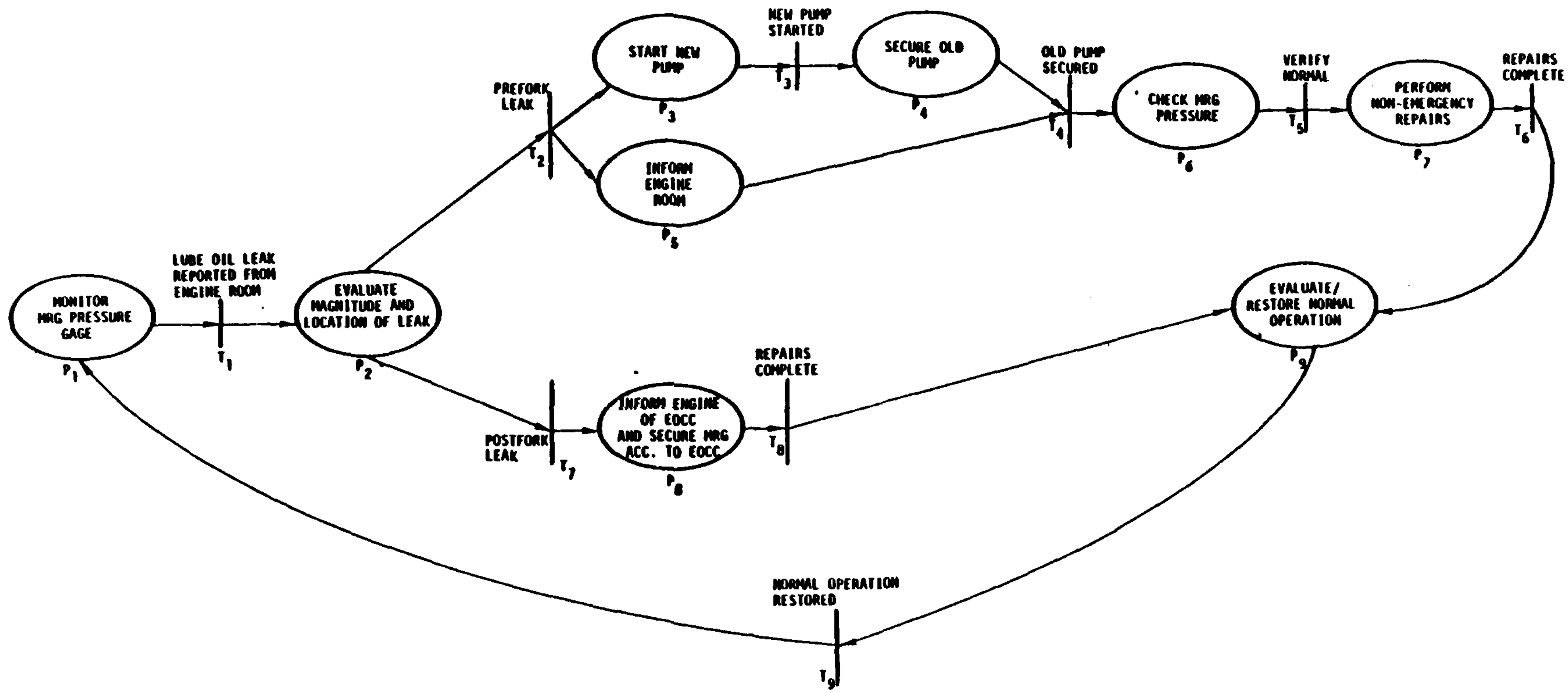


FIGURE 7. .
ILLUSTRATIVE EXAMPLE: PRESCRIPTION EPN FOR LUBE OIL PROBLEM

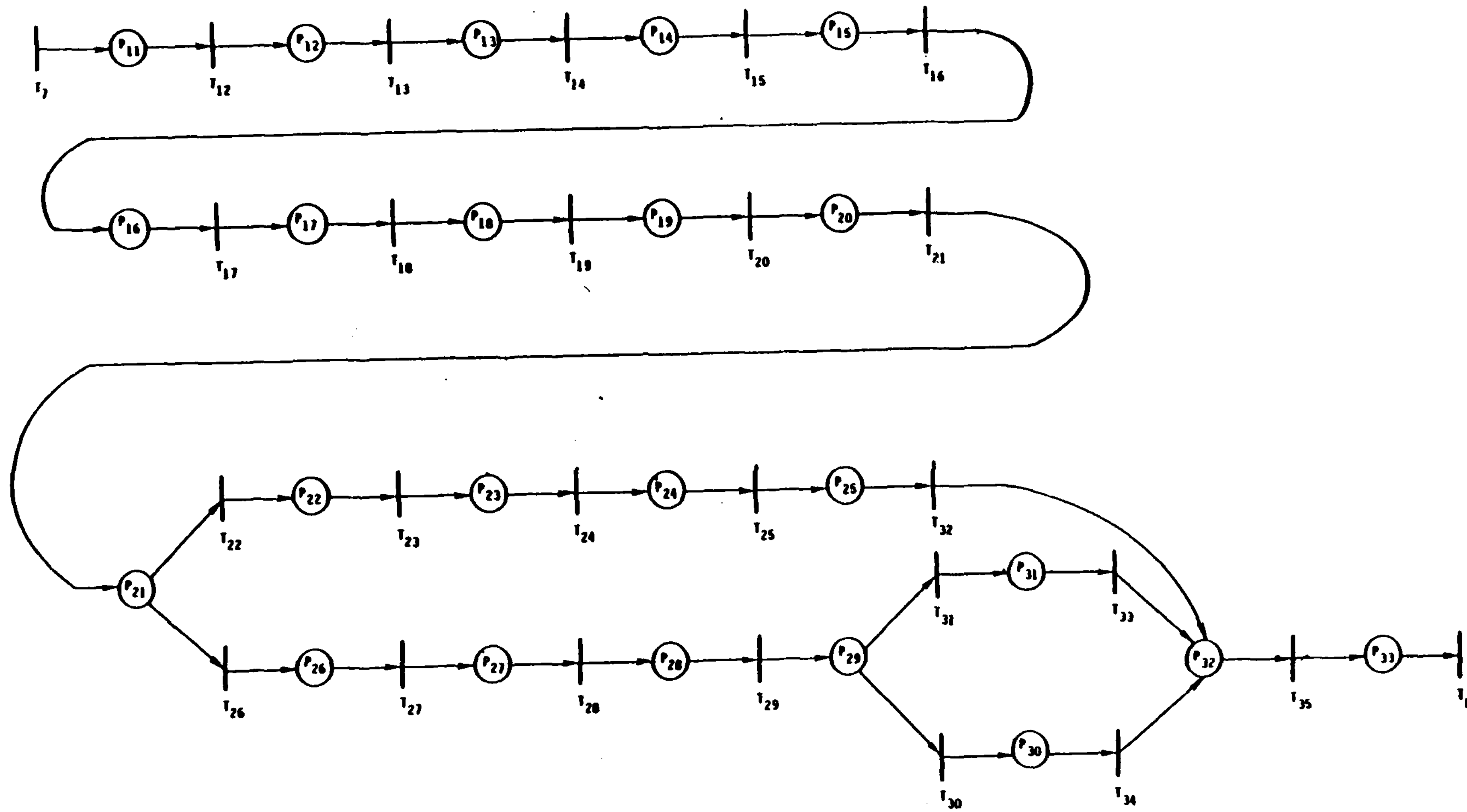


FIGURE 8.
HIERARCHICAL EXPANSION OF P_8

TRANSITIONS

Transition #	Action	Arcs From	Arcs To	Text
T_{12}	YES	P_{11}	P_{12}	PACC operator report to EOOW, "No __ lubeoil service system secured. No __ GTM stopped. It is at CCS. No __ shaft stopped with shaft brake on.
T_{13}	YES	P_{12}	P_{13}	EPCC operator report to EOOW, "No __ GTG is stopped. No __ GTG is online and in parallel with No __ GTG."
T_{14}	YES	P_{13}	P_{14}	Engineering space report manned.
T_{15}	YES	P_{14}	P_{15}	No __ engine room report to EOOW, "Main reduction gear lube oil service system leak is isolated."
T_{16}	YES	P_{15}	P_{16}	PACC operator report to EOOW, "Bleed air secure from No __ GTM and isolated from No 3 GTG."
T_{17}	YES	P_{16}	P_{17}	Unaffected engine room report to EOOW, "Bleed air secured from No __ GTG."
T_{18}	YES	P_{17}	P_{18}	No __ engine room report to EOOW, "Lube oil flushed into bilges; covering with AFFF."
T_{19}	YES	P_{18}	P_{19}	OOD grants permission.
T_{20}	YES	P_{19}	P_{20}	No __ engine room report to EOOW, "Fire hazards removed."
T_{21}	YES	P_{20}	P_{21}	No __ engine room report to EOOW cause of the casualty and estimated time to repair.
T_{22}	NO	P_{21}	P_{22}	Casualty cannot be restored in a reasonable amount of time.
T_{23}	YES	P_{22}	P_{23}	OOD grants permission to stop the ship.
T_{24}	YES	P_{23}	P_{24}	When the SHIP SPEED indicator is at "0" knots, PACC operator report to EOOW, "ITC lever is at 'stop' maintaining zero thrust on No __ shaft."

TRANSITIONS

Transition #	Action	Arcs From	Arcs To	Text
T_{25}	YES	P_{24}	P_{25}	PACC operator report to EOOW, "No __ shaft brake is released."
T_{26}	NO	P_{21}	P_{26}	Casualty can be restored in a reasonable amount of time.
T_{27}	YES	P_{26}	P_{27}	PACC operator report to EOOW, "Throttle control in 'AUTO'."
T_{28}	YES	P_{27}	P_{28}	OOD orders EOOW to transfer ITC control to the pilothouse.
T_{29}	YES	P_{28}	P_{29}	PACC operator transfers ITC control to the pilothouse.
T_{30}	NO	P_{29}	P_{30}	Affected engine was operating above 7500 RPM gas generator speed for all or part of the five minutes preceding shutdown.
T_{31}	NO	P_{29}	P_{31}	Affected engine was operating at or below 7500 RPM gas generator speed for five minutes or more preceding the shutdown (emergency stopped).
T_{32}	NO	P_{25}	P_{32}	Shutdown complete.
T_{33}	NO	P_{31}	P_{32}	Shutdown complete.
T_{34}	NO	P_{30}	P_{32}	Shutdown complete.

PLACES

Place #	Action	Arcs From	Arcs From	Text
P_{11}	YES	T_7	T_{12}	EOOW order engineering spaces manned.
P_{12}	YES	T_{12}	T_{13}	EOOW report to OOD, "Major lube oil leak in No __ engine room. No __ GTM is stopped, ITC is at CCS. No __ shaft is stopped with shaft brake on. Maximum speed is __ knots."
P_{13}	YES	T_{13}	T_{14}	Monitor.
P_{14}	YES	T_{14}	T_{15}	Monitor.
P_{15}	YES	T_{15}	T_{16}	Monitor.
P_{16}	YES	T_{16}	T_{17}	Monitor.
P_{17}	YES	T_{17}	T_{18}	Monitor.
P_{18}	YES	T_{18}	T_{19}	EOOW report to OOD, "Major lube oil leak in No __ engine room is isolated. Lube oil in No __ engine room is flushed into bilges and covered with AFFF." EOOW request permission from OOD to remove fire hazards (in accordance with current environmental protection requirements).
P_{19}	YES	T_{19}	T_{20}	EOOW orders No __ engine room to remove fire hazard (in accordance with current environmental protection requirements).
P_{20}	YES	T_{20}	T_{21}	EOOW report to OOD, "Fire hazards removed from No __ engine room." EOOW order No __ engine room to investigate for the cause of the casualty using approved maintenance procedures and technical
P_{21}	YES	T_{21}	T_{22} T_{26}	EOOW report to OOD the cause of the casualty and estimated time to repair.
P_{22}	YES	T_{22}	T_{23}	EOOW request permission from OOD to stop the ship to lock No __ shaft.

PLACES

Place #	Action	Arcs From	Arcs From	Text
P_{23}	YES	T_{23}	T_{24}	EOOW order PACC operator to place the unaffected shaft ITC lever at "STOP" and maintain zero thrust.
P_{24}	YES	T_{24}	T_{25}	EOOW order PACC operator to release the shaft brake on the affected shaft.
P_{25}	YES	T_{25}	T_{32}	EOOW lock No __ shaft.
P_{26}	YES	T_{26}	T_{27}	EOOW order PACC operator to shift throttle control to "AUTO."
P_{27}	YES	T_{27}	T_{28}	EOOW report to OOD, "Throttle control in 'AUTO'. CCS is standing by to transfer ITC control to the pilothouse."
P_{28}	YES	T_{28}	T_{29}	EOOW order PACC operator to transfer ITC control to the pilothouse.
P_{29}	YES	T_{29}	T_{31} T_{30}	EOOW report to OOD, "ITC control transferred to the pilothouse."
P_{30}	YES	T_{30}	T_{32}	EOWW order PACC operator to cool down affected GTM.
P_{31}	NO	T_{31}	T_{32}	No orders.
P_{32}	YES	T_{32} T_{33} T_{34}	T_8	Repairs proceeding.

Net Execution

The net executes by moving tokens through a sequence of places (activities). The execution of the net is non-unique. It is a function of which transitions fire. With respect to the illustrative example there are two possible paths, p_1 and p_2 (Figure 7).

Path P_1: $P_1 \to T_1 \to P_2 \to T_7 \to P_8 \to T_8 \to P_9 \to T_9 \to P_1$

Path P_2:

$$\begin{tikzcd}[column sep=small] & & & & P_3 \arrow[r] & T_3 \arrow[r] & P_4 \arrow[dr] & & & & & & & & \\ P_1 \arrow[r] & T_1 \arrow[r] & P_2 \arrow[r] & T_2 \arrow[dr] & & & & T_4 \arrow[r] & P_6 \arrow[r] & T_5 \arrow[r] & P_7 \arrow[r] & T_6 \arrow[r] & P_9 \arrow[r] & T_9 \arrow[r] & P_1 \\ & & & & P_5 \arrow[urrr] & & & & & & & & & & \end{tikzcd}$$

Performance Measures

Several performance measures associated with the lube oil leak recovery task (Figure 7) can be used to evaluate both fractional and global task performance. These include:

(1) Event-Related Measures

- Failure to react to lube oil leak in time interval t since receipt of report.
- Failure to evaluate type of leak before proceeding with corrective action.
- Failure to check MRG pressure after securing old pump.
- Failure to verify normal operation at the end of recovery sequence.

(2) Time-Based Measures (associated with activities that have internal completion events).

- Time to react to lube oil leak report.
- Time to ascertain location and magnitude of leak.
- Time to start new pump.
- Time to secure old pump.
- Time to check MRG pressure after securing old pump.
- Time to perform non-emergency repairs.
- Time to secure MRG according to EOCC.
- Time to evaluate/restore normal operation.

(3) Incorrect Responses (extraneous steps, i.e., response to spurious events/execution of redundant actions observed in actual/simulated task performance or elicited from the operator/maintainer in "think-aloud" session or during post-exercise interview).

(4) Procedure-Related Measures. These measures are associated with failure to follow required steps indicated in EOSS/EOCC, for example, steps associated with expansion of P_8 in Figure 8. Specific examples include:

- Failure to issue specific order to Officer on the Deck (OOD).
- Failure to request specific permission from OOD.
- Failure to make specific report following initial incident.

Workload Estimation

The instantaneous workload associated with each of these paths is generally different. A sample execution of the net of the illustrative example is given in the printout (Appendix D). Each transition that "fires" is shown along with its firing time and the resultant token positions. Figures 9 and 10 provide sample profiles of the instantaneous and cumulative workload profiles associated with Path P_1 of the illustration problem.

3.4 MPN-Based Task Concurrency and Workload Analysis

Thus far, the MPN modelling approach has been presented as a means for characterizing maximum workload levels. In this section, it will be shown how these models can be used to expose possible task concurrencies when performing missions. It will also be shown that at the lowest or next to the lowest level of abstraction in the MPN, each activity and combination of activities can be assigned reliable workload ratings by experts (Madni and Lyman, 1983). A discussion of possible sources of workload is provided in Appendix F. Since an MPN model may be hierarchically expanded in increasing levels of detail, it is possible to expand the net to the man-machine interaction (MMI) level when representing a shipboard propulsion systems maintenance task. Examples of the lower level of such an expansion for the lube oil problem handling are given in Figure 2 and 3.

Workload values can be subjectively elicited from experts either at this level or at the next highest level. Engineering officers or journeymen who have performed such tasks feel comfortable assigning workload values to the individual activities or combination of activities described at these levels. In addition, the minimum and maximum time required to perform each activity are elicited from the experts. These execution times are necessary to compute the possible combination of activities that need to be performed concurrently. This is illustrated in the abstract net and table

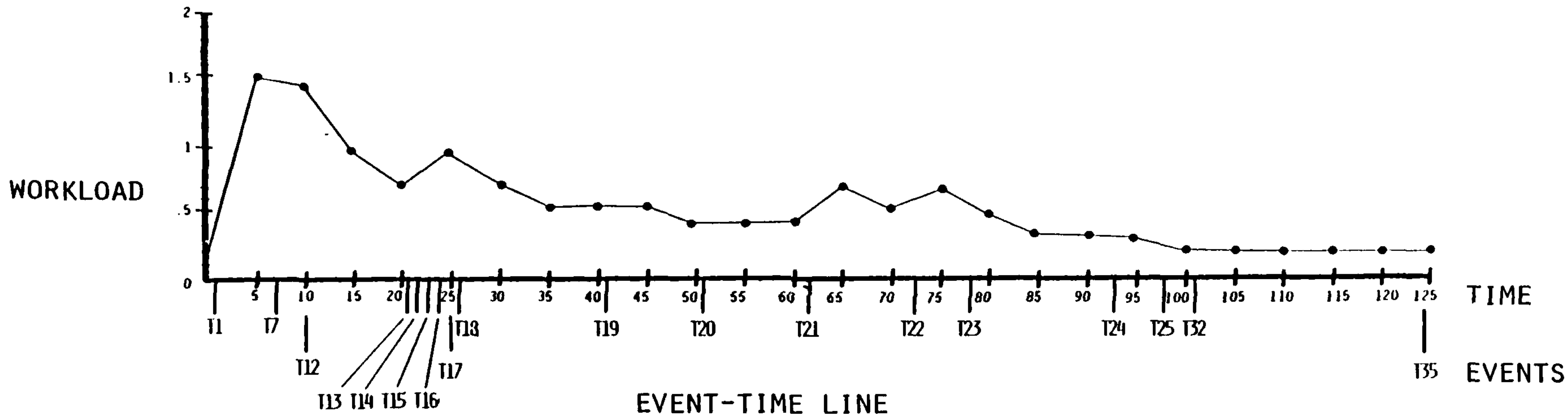


FIGURE 9.
INSTANTANEOUS WORKLOAD PROFILE

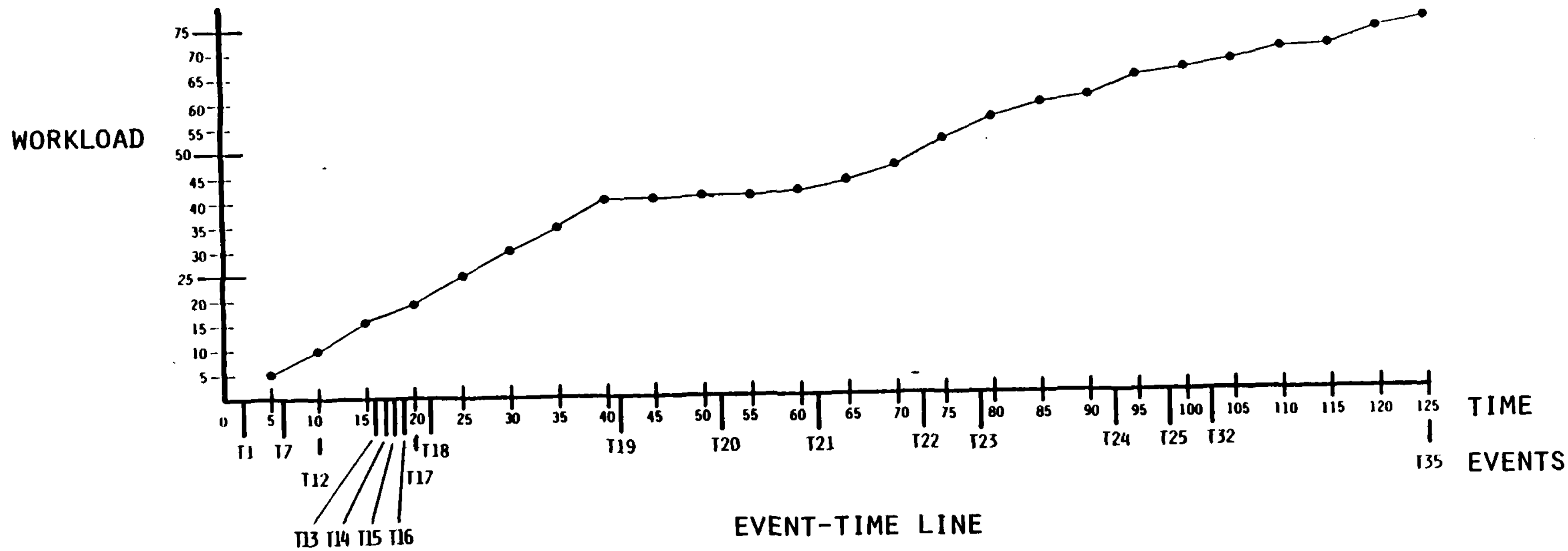


FIGURE 10.
CUMULATIVE WORKLOAD PROFILE

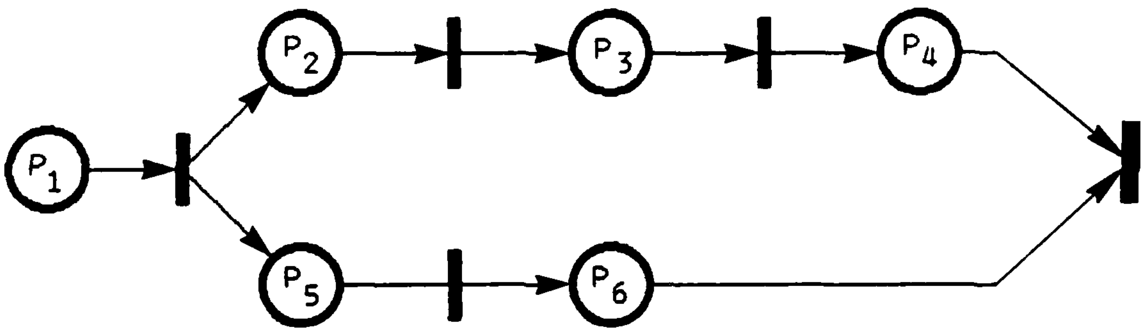
of Figure 11. In order to illustrate this principle, we take two possible scenarios for this net and look at the particular conjunction of activities required in each case. Suppose that the following times are taken by activities P2-P6:

Activity	Average Execution Time (sec)
P_2	10
P_3	10
P_4	1
P_5	10
P_6	10

Then, the only conjunctions that would occur would be P1, P2 ∧ P5, P3 ∧ P6 and P4, where '∧' represents conjunction. On the other hand, let us say that the execution times were as follows:

Activity	Average Execution Time (sec)
P_2	1
P_3	2
P_4	2
P_5	10
P_6	10

Then, the only conjunctions that would occur would be P1, P2 ∧ P5, P3 ∧ P5, P4 ∧ P5, P5, and P6. These two scenarios yield different overall workloads.



Task	Minimum Time (sec)	Maximum Time (sec)
P1	10	100
P2	1	15
P3	2	10
P4	1	10
P5	10	15
P6	10	15

FIGURE 11.
INDETERMINATE CONCURRENCY IN AN MPN

The process of generating conjunctions involves "executing" the MPN (either manually or via computer simulation) using the execution times related to the activities. The complete MPN, task descriptions, and primitive execution times can be elicited from experts.

Any connected subsection of an MPN is a subnet of that MPN. Some sample subnets of an MPN are given in Figure 6. With respect to this figure, it is easy to see how we could consider the subnet obtained by deleting Path 2_1. If we found that the workloads over the new subnet were sufficiently reduced from those of the original MPN, the subnet Path 2, would be a good candidate for performance enhancement or automation.

For purposes of workload analysis, subnets that are complements of other subnets (which have been tentatively selected for automation), can be isolated. To investigate the workload reduction attributed to each candidate for performance enhancement (e.g., interface redesign or maintainability aids) it is necessary in the proposed analysis scheme to *consider candidate subnets for enhancement* and look at the complement nets to these subnets. By obtaining workload values for the entire net and all the complement subnets, one can decide which subnets should be considered for possible enhancement.

As Figure 11 indicates, an MPN without execution times is often inadequate to determine all the conjunctions of tasks that could occur simultaneously. Using Figure 11 and the minimum and maximum execution times for the places, we can obtain the following lists of possible task conjunctions and non-conjunctions:

1. P1, P2 and P5, P3 and P6, P4
2. P1, P2 and P5, P3 and P5, P4 and P6, P6
3. P1, P2 and P5, P3 and P5, P4 and P5, P6
4. P1, P2 and P5, P3 and P5, P4 and P5, P5, P6
5. P1, P2 and P5, P2 and P6, P3 and P6, P4
6. P1, P2 and P5, P2 and P6, P3 and P6, P3, P4
7. P1, P2 and P5, P2 and P6, P3 and P6, P4 and P6, P6, etc.

To obtain an exhaustive list of all concurrencies and non-concurrencies, it is necessary to run a large number of Monte Carlo simulations of the MPN with execution times for places varying between the minimum and maximum execution times. In general, running Monte Carlo simulations are necessary, unless the net is simple enough so that all task concurrencies and non-concurrencies can be enumerated by inspection or alternatively listed by an expert with the ability/experience to recall all contingencies.

The process of getting all concurrencies and non-concurrencies must be repeated for every complement subnet before selecting a candidate subnet for enhancement. Once all of the concurrencies and non-concurrencies for each complement subnet and candidate subnet as well as the full net have been identified, workload values can be elicited from an expert for each task combination in the list. This provides a report of the instantaneous workloads possible with and without various possible enhanced subnets. One can then use these subjective workload values to decide on which subnet to enhance. The value of workload elicited for each situation should be on a relative scale of 0 of high difficulty should be defined by the expert on this scale.

Certain subnets will have complement subnets in which the higher values of workload are considerably less than for the full net. These subnets are potential candidates for enhancement. Particularly, when all or most of the workloads fall below the expert-defined threshold for the complement of a subnet, one can feel fairly confident that if the subnet is enhanced or automated, the remaining tasks will be "do-able" by the operator/maintainer.

3.5 Projected Analysis of Navy Maintenance Data

CASREP and 3M Reports covering the Main gas Turbine Propulsion System for the DD963 class of ship for the period January 1980 through December 1982 have been received from the Navy Maintenance Support Center and the Navy Ship Parts Control Center, Mechanicsburg, PA. Analysis of these data is currently in progress and the results will be reported in a subsequent technical report. These data will be analyzed to determine their potential as a data source for confirming the data elicited from subject matter experts and for validating the MPN model.

4. PETRICONTROL SOFTWARE PACKAGE

The PETRICONTROL package accepts a user-defined task within an MPN representation, executes it, and prints out net execution and workload information. The user defines the net at the logical level by creating a file containing the requisite information in character format. The required information is specified below and must be provided in the indicated order and format with one or more blanks or carriage returns between adjacent values (note-- multiple value fields and text are followed by a semicolon):

@, Label, type of node, subtype, associated Boolean expression, hierarchical level, basic workload weight, workload decay half-life, forward arcs, backward pointers, hierarchical down-pointer, hierarchical up-pointer, inhibition arcs (other end), text. The last record is followed by @@.

Label. The label consists of up to 9 characters for the current place or transition.

Type of Node. The type is specified as P for place or T for transition.

Subtype. Possible subtypes with associated codes are:

-Place

-1	Monitor until event
n $\geq$p 0	Activity requiring n seconds

-Transition

0	Internal completion
1	External event or condition
2	Mixed (internal completion and/or external event or condition

Associated Boolean Expression. This must be 0 for a place but gives the firing conditions for a transition (see Figure 12 below).

IC	Internal completion	
En	External event n	$n \geq 0$
Cn	External condition n	$n \geq 0$
$IC \wedge En$, $IC \vee En$	Mixed expression	
$IC \wedge Cn$, $IC \vee Cn$	Mixed expression	

Figure 12. Firing Conditions for Transitions

Hierarchical Level. This is the level in the hierarchy of the current node in the Petri Net. The levels start at 1 and increase as you go lower (i.e., down) in the hierarchy.

Basic Workload Weight. The workload weight for a place or transition is a floating-point number. The weights are provided in Table 5.

-Places	
Passive	.1
Active	
Skill based	.3
Rule based	.4
Knowledge based	.7
-Transitions	
Internal completion	.1
External	
Expected	.2
Unexpected (containable)	.5
Unexpected (catastrophic)	1.0
Mixed	
Add respective components such as Internal Completion + External Expected = .1 + .2 = .3	

Table 5. Workload Weights for Places and Transitions

Workload Decay Halflife. The workload contributions of transitions follow an exponential decay with time. The numbers of seconds for the halflife of these decay processes are specified in Table 6 below:

Transition Type	Halflife (in seconds)
Internal completion	1
External	
Expected	2
Unexpected (containable)	4
Unexpected (catastrophic)	10
This value is set to 0 for places.	

Table 6. Halflife for Exponentially Decaying Transition-Related Loads

<u>Forward Arcs</u>. The nodes pointed at by the forward arcs leaving the current node are specified by their labels. Up to 10 arcs are allowed.

<u>Backward Pointers</u>. The nodes with arcs pointing to the current node are specified by their labels. Up to 10 arcs are allowed.

<u>Hierarchical Down-Pointer</u>. If the current node has an hierarchical expansion, the label of the first node of that expansion is provided.

<u>Hierarchical Up-Pointer</u>. If the current node is the final node in an hierarchical expansion of a higher level node, then the label of that higher level node is given here.

<u>Inhibition Arcs</u>. If the current node has any inhibition arcs coming into it or leaving it, the labels of the other ends of those arcs is given here. Up to 10 labels may be used.

<u>Text</u>. Up to 359 characters of text describing the current node may be specified here.

An example logical data file follows (see Figure 13). To illustrate more clearly how to enter such a file, find T2 six lines down in the file and interpret it as follows:

Label = T2, Type = T, Sub-type = 2, Boolean Expression = IC&C1, Level = 1, Weight = 0.3, Halflife = 3, Forward nodes are P3 and P5, Backpointer is P2, there are no hierarchical or inhibition pointers, and the text is "Prefork leak."

```
Jun 23 15:04 1983  PETRIdata Page 1

@ P1   P  -1 0         1 0.1  0 T1;          T9;            0    0    0;
Monitor MRG pressure gauge.;
@ T1   T   1 E1        1 1.0 10 P2;          P1;            0    0    0;
Engine room reports major lube oil leak in MRG lube oil system.;
@ P2   P   5 0         1 0.7  0 T2 T7;       T1;            0    0    0;
Evaluate magnitude and location of leak.;
@ T2   T   2 IC&C1     1 0.3  3 P3 P5;       P2;            0    0    0;
Prefork leak.;
@ P3   P   5 0         1 0.3  0 T3;          T2;            0    0    0;
Start new pump.;
@ T3   T   0 IC        1 0.1  1 P4;          P3;            0    0    0;
New pump started.;
@ P4   P   5 0         1 0.3  0 T4;          T3;            0    0    0;
Secure old pump.;
@ P5   P   5 0         1 0.3  0 T4;          T2;            0    0    0;
Inform engine room.;
@ T4   T   0 IC        1 0.1  1 P6;          P4 P5;         0    0    0;
Old pump secured and engine room informed.;
@ P6   P   5 0         1 0.3  0 T5;          T4;            0    0    0;
Check MRG pressure.;
@ T5   T   0 IC        1 0.1  1 P7;          P6;            0    0    0;
Verify normal.;
@ P7   P  15 0         1 0.3  0 T6;          T5;            0    0    0;
Perform non-emergency repairs.;
@ T6   T   0 IC        1 0.1  1 P9;          P7;            0    0    0;
Repair complete.;
@ T7   T   2 IC&C2     1 0.3  3 P8;          P2;            0    0    0;
Post fork leak.;
@ P8   P  -1 0         1 0.0  0 T8;          T7;            P11 0    0;
Inform engine room of EOCC.;
@ T8   T   0 IC        1 0.1  1 P9;          P8;            0    0    0;
Engine room informed and repairs complete.;
@ P9   P   2 0         1 0.7  0 T9;          T6 T8;         0    0    0;
Evaluate/restore normal operation.;
@ T9   T   0 IC        1 0.1  1 P1;          P9;            0    0    0;
Normal operation restored.;
@ P11 P    2 0         2 0.3  0 T12;         T7;            0    0    0;
EOW orders engineering spaces manned.;
@ T12 T    2 IC&E2     2 0.3  3 P12;         P11;           0    0    0;
PACC operator reports to EOW, "No. i lube oil service system secured.
No. i GTM stopped. It is at CCS.  No. i shaft stopped with shaft brake
on.";
@ P12 P   10 0         2 0.4  0 T13;         T12;           0    0    0;
EOW reports to OOD, "Major lube oil leak in no. i engineroom.  No. i
GTM is stopped.  ITC is at CCS.  No. i shaft is stopped with shaft
brake on.  Maximum speed available is i knots.";
@ T13 T    2 IC&E3     2 0.3  3 P13;         P12;           0    0    0;
EPCC operator reports to EOW, "No. i GTG is stopped.  No. i GTG is
online and in parallel with no. i GTG.";
@ P13 P   -1 0         2 0.1  0 T14;         T13;           0    0    0;
Monitor.;
@ T14 T    1 E4        2 0.2  2 P14;         P13;           0    0    0;
Engineering spaces report manned.;
@ P14 P   -1 0         2 0.1  0 T15;         T14;           0    0    0;
Monitor.;
@ T15 T    1 E5        2 0.2  2 P15;         P14;           0    0    0;
```

FIGURE 13.
LOGICAL PETRI NET FOR ILLUSTRATIVE PROBLEM

```
No. i engineroom reports to EOW, "Main reduction gear lube oil service
system leak is isolated.";
@ P15 P  -1 0        2 0.1  0 T16;         T15;          0   0   0;
Monitor.;
@ T16 T   1 E6       2 0.2  2 P16;         P15;          0   0   0;
PACC operator reports to EOW, "Bleed air secured from no. i GTM and
isolated from no. 3 GTG.";
@ P16 P  -1 0        2 0.1  0 T17;         T16;          0   0   0;
Monitor.;
@ T17 T   1 E7       2 0.2  2 P17;         P16;          0   0   0;
Unaffected engineroom reports to EOW, "Bleed air secured from no. i GTG.";
@ P17 P  -1 0        2 0.1  0 T18;         T17;          0   0   0;
Monitor.;
@ T18 T   1 E8       2 0.2  2 P18;         P17;          0   0   0;
No. i engineroom reports to EOW, "Lube oil flushed into bilges, covering
with AFFF.";
@ P18 P  15 0        2 0.4  0 T19;         T18;          0   0   0;
EOW reports to OOD, "Major lube oil leak in no. i engineroom is isolated.
Lube oil in no. i engineroom is flushed into bilges and covered with AFFF."
EOW requests permission from OOD to remove fire hazards (in accordance with
current environmental protection requirements).";
@ T19 T   0 IC       2 0.1  1 P19;         P18;          0   0   0;
OOD grants permission.;
@ P19 P  10 0        2 0.4  0 T20;         T19;          0   0   0;
EOW orders no. i engineroom to remove fire hazards (in accordance with
environmental protection requirements).;
@ T20 T   0 IC       2 0.1  1 P20;         P19;          0   0   0;
No. i engineroom reports to EOW, "Fire hazards removed.";
@ P20 P  10 0        2 0.4  0 T21;         T20;          0   0   0;
EOW reports to OOD, "Fire hazards removed from no. i engineroom." EOW orders
no. i engineroom to investigate for the cause of the casualty using approved
maintenance procedures and technical manuals.;
@ T21 T   2 IC&E9    2 0.3  3 P21;         P20;          0   0   0;
No. i engineroom reports to EOW cause of the casualty and estimated time to
repair.;
@ P21 P  10 0        2 0.4  0 T22 T26;     T21;          0   0   0;
EOW reports to OOD the cause of the casualty and estimated time to repair.;
@ T22 T   2 IC&E10   2 0.5  5 P22;         P21;          0   0   0;
Casualty cannot be restored in a reasonable amount of time.;
@ P22 P   5 0        2 0.3  0 T23;         T22;          0   0   0;
EOW requests permission from OOD to stop the ship to lock no. i shaft.;
@ T23 T   0 IC       2 0.1  1 P23;         P22;          0   0   0;
OOD grants permission to stop the ship.;
@ P23 P  15 0        2 0.3  0 T24;         T23;          0   0   0;
EOW orders PACC operator to place the unaffected shaft ITC lever at 'STOP'
and maintain zero thrust.;
@ T24 T   0 IC       2 0.1  1 P24;         P23;          0   0   0;
When the SHIP SPEED indicator is at "0" knots, PACC operator reports to EOW,
"ITC lever is at 'STOP'.  Maintaining zero thrust on no. i shaft.";
@ P24 P   5 0        2 0.3  0 T25;         T24;          0   0   0;
EOW orders PACC operator to release the shaft brake on the affected shaft.;
@ T25 T   0 IC       2 0.1  1 P25;         P24;          0   0   0;
PACC operator reports to EOW, "No. i shaft brake is released.";
@ P25 P   3 0        2 0.3  0 T32;         T25;          0   0   0;
EOW locks no. i shaft.;
@ T32 T   2 IC       2 0.1  1 P32;         P25;          0   0   0;
```

FIGURE 13 (CONT'D)

```
Shutdown complete.;
@ T26 T    2 IC&E11    2 0.3  3 P26;          P21;            0    0    0;
Casualty can be restored in a reasonable amount of time.;
@ P26 P    5 0         2 0.3  0 T27;          T26;            0    0    0;
EOW orders PACC operator to shift throttle control to 'AUTO'.;
@ T27 T    0 IC        2 0.1  1 P27;          P26;            0    0    0;
PACC operator reports to EOW, "Throttle control in 'AUTO'.";
@ P27 P   10 0         2 0.3  0 T28;          T27;            0    0    0;
EOW reports to OOD, "Throttle control in 'AUTO'.  CCS is standing by to
transfer ITC control to the pilothouse.";
@ T28 T    0 IC        2 0.1  1 P28;          P27;            0    0    0;
OOD orders EOW to transfer ITC control to the pilothouse.;
@ P28 P   10 0         2 0.3  0 T29;          T28;            0    0    0;
EOW orders PACC operator to transfer ITC control to the pilothouse.;
@ T29 T    0 IC        2 0.1  1 P29;          P28;            0    0    0;
PACC operator transfers ITC control to the pilothouse.;
@ P29 P    5 0         2 0.3  0 T31 T30;      T29;            0    0    0;
EOW reports to OOD, "ITC control transferred to the pilothouse.";
@ T31 T    2 IC&C3     2 0.3  3 P31;          P29;            0    0    0;
Affected engine was operating at or below 7500 RPM gas generator speed for
five minutes or more preceding the shutdown (emergency stopped).;
@ P31 P    1 0         2 0.3  0 T33;          T31;            0    0    0;
No orders.;
@ T33 T    1 IC        2 0.1  1 P32;          P31;            0    0    0;
Shutdown complete.;
@ T30 T    2 IC&C4     2 0.3  3 P30;          P29;            0    0    0;
Affected engine was operating above 7500 RPM gas generator speed for all or
part of the five minutes preceding shutdown.;
@ P30 P    3 0         2 0.3  0 T34;          T30;            0    0    0;
EOW orders PACC operator to cool down affected GTM.;
@ T34 T    2 IC&E12    2 0.3  3 P32;          P30;            0    0    0;
Shutdown complete.;
@ P32 P   25 0         2 0.3  0 T35;          T32 T33 T34;    0    0    0;
Repairs proceeding.;
@ T35 T    0 IC        2 0.0  0 P33;          P32;            0    0    0;
Dummy complete.;
@ P33 P    0 0         2 0.0  0 T8;           T35;            0    P8   0;
Dummy zero-wait hold.;
@@
```

FIGURE 13 (CONT'D)

Additional Input

At this stage, there is no world model, yet events and conditions must occur in some way. The present scenario generator looks for the presence of tokens in some precursor place to set an event or condition to true. The data structures that must be specified are 'condlist', 'eventlist', and 'evcnmak'. 'Condlist' and 'eventlist' are the lists for all defined conditions and events, respectively, with their associated truth values (initialized to 'F' for false). 'Evcnmak' provides an association between alternative events and conditions and their associated precursor places. These structures in the external file are illustrated in Figure 14.

Output

If the user specifies one run at a time when a Petri Net is executed, PETRICONTROL gives the transitions as they fire and the time of firing, each successive marking, and finally, instantaneous and cumulative workload. If the user wants just the average workload for the task, 100 passes (executions of the net) are performed and the final cumulative average workload is printed. A sample printout is given in Appendix C.

```
/*      petriext.c
    6/6/83--Denis D. Purcell

        PROCEDURE:
                External globals definition.

        PURPOSE:
                Defines all externals needed for Petri net
                implementation.

                                                                        */

/*      Petri net structure.                                            */
        struct  petrinet
                {       char    label[10];
                        char    type;
                        short   stype;
                        short   inprocess;
                        char    prop[20];
                        short   tokens;
                        short   level;
                        short   tokenlevel;
                        float   weight;
                        short   halflife;
                        short   farcs[10];
                        short   bptrs[10];
                        short   dptr;
                        short   uptr;
                        short   inhibs[10];
                        char    text[360];
                };
        struct  petrinet        maintain[100];
/*      Structure location of Petri net nodes.                          */
        char    labeltable[100][10];
/*      History of markings in net.                                     */
        struct  petrimark
                {       short   index;
                        short   tokens;
                        char    label[10];
                        short   level;
                };
        struct  petrimark       histmark[100][20];
/*      History of marking times.                                       */
        short   histmtime[100];
/*      Current history index, last print index,  and elapsed time.     */
        int     histind;
        int     lastprint;
        int     elapsdtime;
/*      History of transitions fired in net.                            */
        struct  petritran
                {       short   index;
                        char    label[10];
                        short   level;
                };
        struct  petritran       histtran[100][20];
```

FIGURE 14.
MPN INPUT STRUCTURE

```
/*      History of transition times index.                                  */
        int     htransind;
/*      History of transition times.                                        */
        short   htranstime[100];
/*      List of conditions and their truth values.                          */
        struct  rwlist
                {       char    label[10];
                        char    tvalue;
                }       condlist[100] =
/*      Initialize condlist.                                                */
                {"C1\0          ",'F',"C2\0          ",'F',"C3\0          ",'F',
                 "C4\0          ",'F',"\0          "};
/*      List of events and their truth values.                              */
        struct  rwlist  eventlist[100] =
/*      Initialize eventlist.                                               */
                        {"E1\0          ",'F',"E2\0          ",'F',
                         "E3\0          ",'F',"E4\0          ",'F',
                         "E5\0          ",'F',"E6\0          ",'F',
                         "E7\0          ",'F',"E8\0          ",'F',
                         "E9\0          ",'F',"E10\0         ",'F',
                         "E11\0         ",'F',"E12\0         ",'F',
                         "\0          "};
/*      Event and condition creation-driving structure.                     */
        struct  crdrv
                {       char    place[10];
                        char    happen[4][10];
                }       evcnmak[100] =
/*      Initialize evcnmak.                                                 */
                {"P1\0          ","E1\0          ","\0          ","\0          ",
                 "\0          ",
                 "P1\0          ","C1\0          ","C2\0          ","\0          ",
                 "\0          ",
                 "P11\0         ","E2\0          ","\0          ","\0          ",
                 "\0          ",
                 "P12\0         ","E3\0          ","\0          ","\0          ",
                 "\0          ",
                 "P13\0         ","E4\0          ","\0          ","\0          ",
                 "\0          ",
                 "P14\0         ","E5\0          ","\0          ","\0          ",
                 "\0          ",
                 "P15\0         ","E6\0          ","\0          ","\0          ",
                 "\0          ",
                 "P16\0         ","E7\0          ","\0          ","\0          ",
                 "\0          ",
                 "P17\0         ","E8\0          ","\0          ","\0          ",
                 "\0          ",
                 "P20\0         ","E9\0          ","\0          ","\0          ",
                 "\0          ",
                 "P21\0         ","E10\0         ","E11\0         ","\0          ",
                 "\0          ",
                 "P29\0         ","C3\0          ","C4\0          ","\0          ",
                 "\0          ",
                 "P30\0         ","E12\0         ","\0          ","\0          ",
                 "\0          ","\0          "};
/*      Instantaneous, cumulative, and full cumulative workloads, and
        average full cumulative workload.                                   */
```

FIGURE 14 (CONT'D)

```
        float   wload[1000],cwload[1000],fcwload[100],afcwload;
```

FIGURE 14 (CONT'D)

5. PRELIMINARY GUIDELINES FOR HUMAN PERFORMANCE ENHANCEMENT

Enhancement of human performance within a man-machine environment system context requires, in general, one or more of the following:

(1) Training, to overcome skills deficiencies.

(2) Task Reallocation, to ensure fair distribution of workload.

(3) Man-machine-interface (MMI) Redesign, to simplify the operator/maintainers interaction with the equipment.

(4) Aiding, to reduce operator burden and enhance operator performance.

Within the context of human factors and human-related problems in maintainability of propulsion systems each of the above can be applicable. Exactly which is warranted in a specific context is shown in Figure 15.

Training is warranted when the maintainer/operator has certain skill deficiencies that can be "trained out." Task Reallocation may be warranted when there is unequal distribution in workloads or when workload of an individual operator is excessively high or low. However, due to equipment (MMI constraints) and/or manpower resource availability, task reallocation may not always be feasible. MMI redesign (or consideration of other MMI options) is another alternative that may be viable, especially when operators are reasonably trained, their workload is not excessive, but their performance is deficient. Finally, aiding is the only recourse when neither redesign nor reallocation is feasible, operators are trained, but workload is excessive and performance is deficient.

Proper training receive priority but may not be always feasible. Task reallocation, if necessary and feasible, is a straightforward solution to performance problems resulting from an individual's workload being excessive or deficient. MMI redesign can have minimal or prohibitive cost

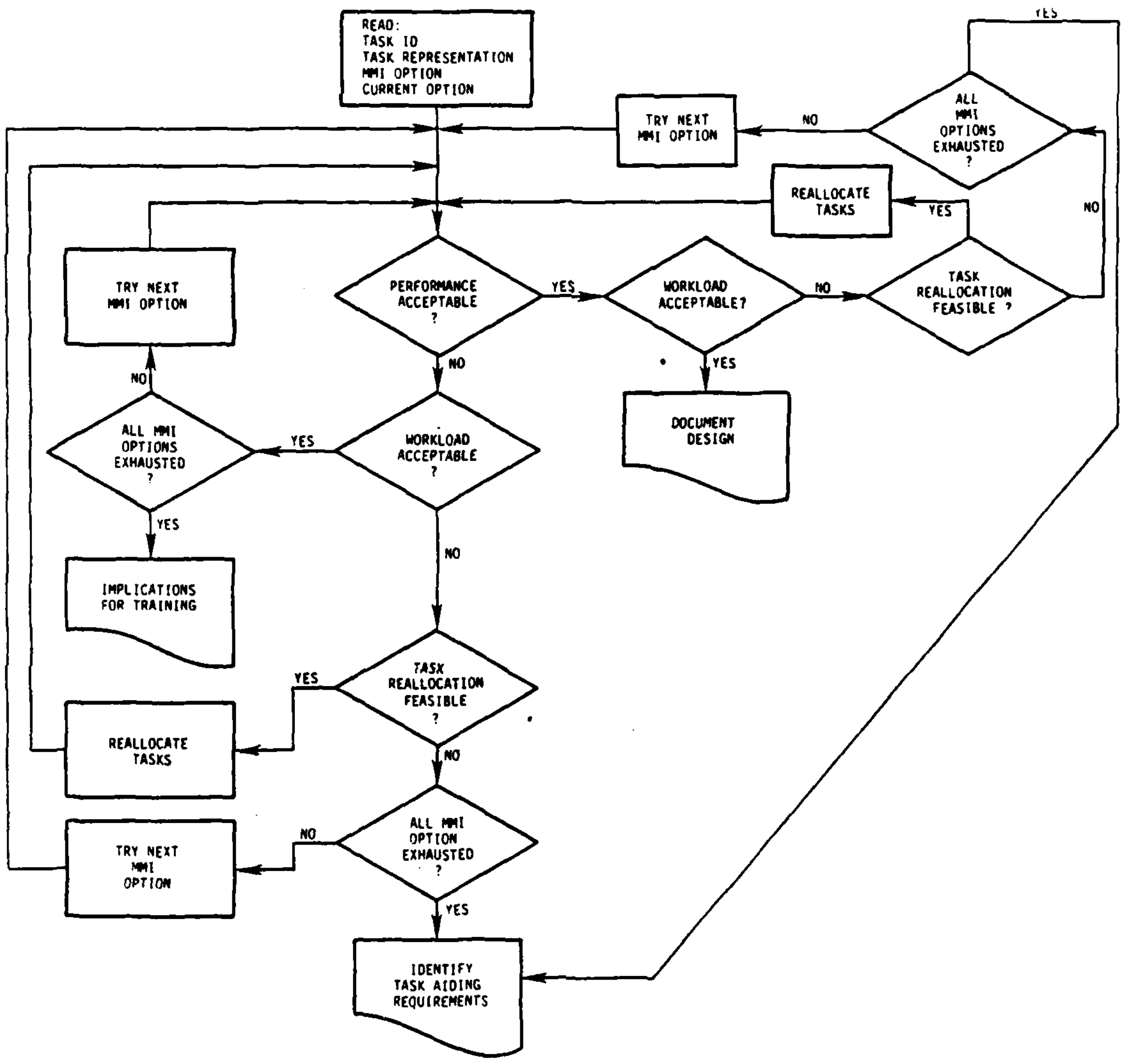


FIGURE 15.
HUMAN PERFORMANCE ENHANCEMENT METHODOLOGY

and time impacts. Further, redesign of the MMI, while perhaps desirable may not appreciably reduce operator workload. Aiding typically is the only recourse available when the others fail. However, aiding typically implies additions/changes to software and occasionally to hardware, too. The overall approach, when partial automation or aiding is necessary, is shown in flowchart form (Figure 15). This figure actually provides an integrated approach for determining which alternative is warranted and when. Figure 16 provides the overall concept for aid selection in flowchart form.

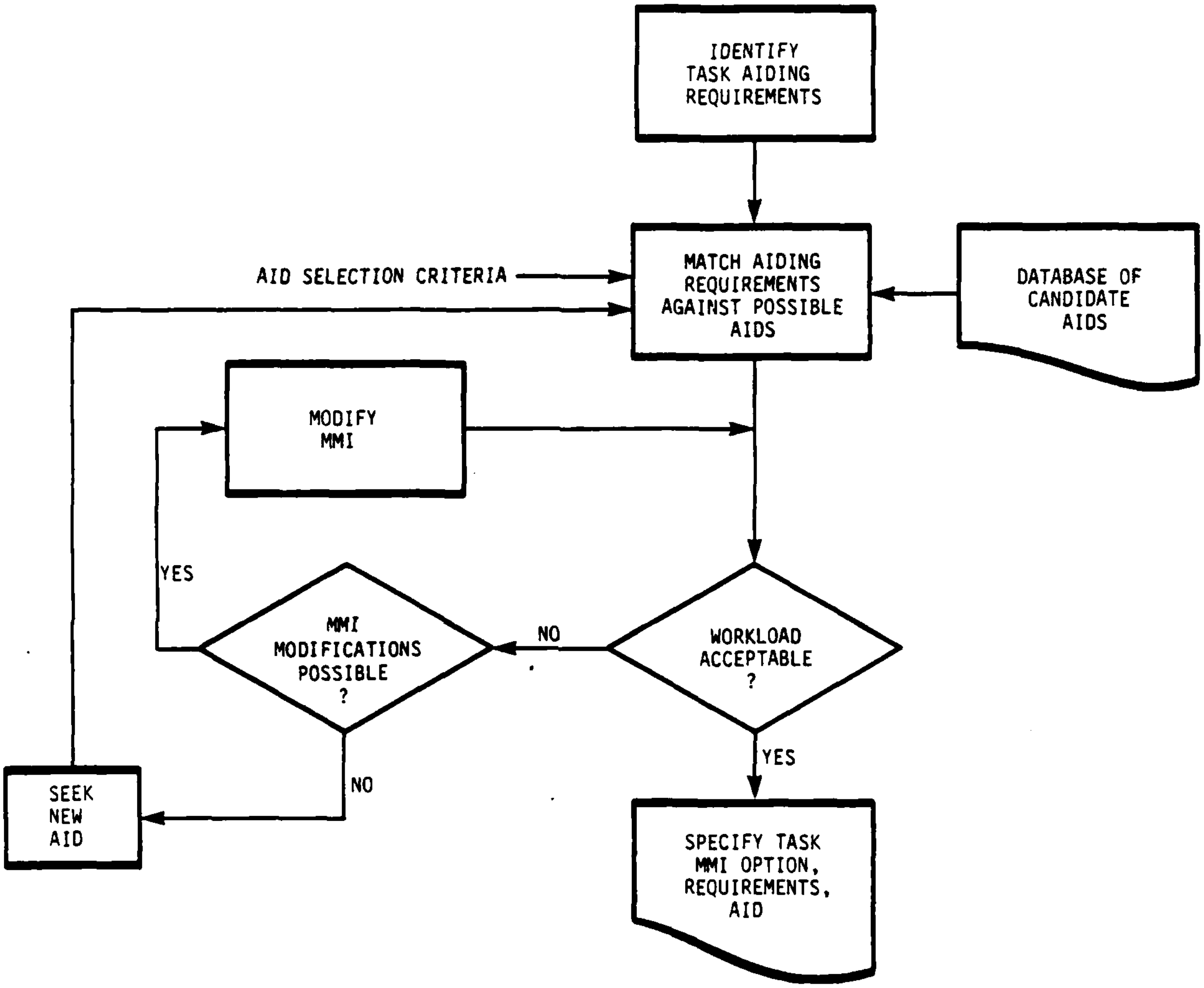


FIGURE 16.

AID SELECTION CONCEPT

6. CONCLUSIONS & FUTURE DIRECTIONS

This study has resulted in a systematic model-based methodology for analyzing operator/maintainer-related maintainability problems associated with shipboard propulsion plants in general and the DD963 class gas turbine system in particular. It has been shown that within this framework several types of human-related problem areas can be predicted/identified. These include: (1) inadequate communication in cooperative maintenance tasks; (2) gaps in operator/maintainer knowledge; (3) operator slips; (4) inadequate MMI design. It has been suggested that problems in cooperative maintenance tasks can often be alleviated by proper and timely presentation of maintenance-related information. It has been shown that the MPN representation lends itself to problem identification, performance evaluation and computer-aided human factors design. At the heart of this approach is a workload prediction/estimation process, the results of which, coupled with operator performance data, can be used to provide the necessary insights in determining whether MMI redesign, task reallocation or aiding is warranted.

In addition to succinctly capturing the input/output data description, a structural MPN model can also provide some indication of the interactions among perceptual, cognitive, and motor processes. In the current model, we have assumed that maximal workload associated with concurrent activities is additive. In future work, we hope to introduce the notion of a finite resource pool, identifying resources required by each kind of activity as a means for determining the total workload associated with various kinds of concurrent activities. Combined with model synthesis techniques and equivalence structures (e.g., Gelenbe and Mitrani, 1980), a structural model could potentially provide both predicted performance characterization and control of a well-represented maintenance task.

Future work in this problem area will include the analysis of maintenance data from historical Navy data bases to confirm predicted problem areas and provide qualitative evaluation. Also field studies will be conducted to collect human performance data which will be used to validate the current model. In addition, the execution of the MPN along with performance measures will be portrayed on a graphics system under microcomputer control to evaluate the model for its potential as a system design tool. The overall approach will be applied to identify specific situations within the selected problem domain where aiding is not just desirable but necessary for adequate man-machine performance. Finally, candidate maintainability aids and MMI redesign requirements for current and future GT systems will be suggested.

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APPENDIX A

THE PETRI NET

Appendix A

The Petri Net

Petri nets are versatile modelling devices for studying the structure and control of concurrent processes. Petri nets originated in petri's dissertation "Communication with Automata" (1962), and have been refined and developed by Holt, Commoner, and others (Holt et al, 1968, 1970; Commoner et al, 1971). Petri nets and related graph models have been used for modelling a wide variety of systems from computers to social systems such as: parallel computation (Miller, 1973 and Agerwala, 1974), asynchronous process corrdination (Noe, 1971 and Thomas, 1976), knowledge representation (Genrich et al, 1976; Zisman, 1978; and Jantzen, 1979), language formulation (Ginsburg, 1966 and Oberquelle, 1979), legal systems (Meldman, 1971, 1978) man-machine systems (Meldman, 1977), and human information processing activities (Schumacker and Geiser, 1978).

The properties, concepts, and techniques of Petri nets are currently being developed and expanded in a search for natural, simple and powerful methods for describing and analyzing the flow of information and control in systems, particularly systems that may exhibit asynchronous and concurrent activities (Petri, 1979; Peterson, 1980). The major use of Petri nets has been the modelling of systems of events in which it is possible forsome events to occur concurrently but there are constraints on the concurrence, precedence, or frequency of these occurrences. In the words of Miller (1973):

> "A Petri net is a graphical representation with directed edges between two different types of nodes. A node represented as a circle is called a place and a node represented by a bar is called a transition. The places in a Petri net have the

capability of hiding tokens. For a given transition, those places that have edges directed into the transition are called input places and those having edges directed out of this transition are called output places for the transition. If all the input places for a transition contain a token, then the transition is said to be active. An active transition may fire. The firing removes a token from each input place and puts a token on each output place. Thus, a token in a place can be used in the firing of only one transition. A simple example of a Petri net is shown in Figure A-1. Here tokens are

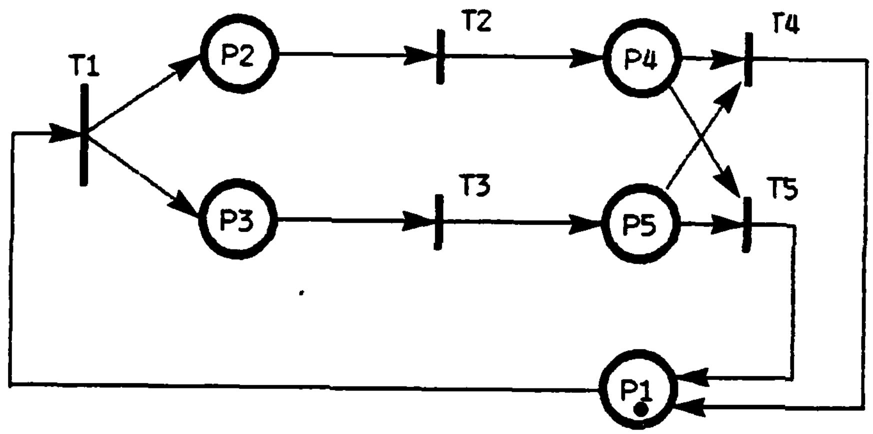

Figure A-1. A Sample Petri Net

shown as black dots. The starting condition has a token only in Place P1. The activity of the net (or process) is then described by the successive firings of transitions. In this example, T1 can fire followed by T2 and T3. Only after both T2 and T3 have fired are T4 and T5 active. Either T4 or T5 can fire but not both. When either T4 or T5 fires it brings the net back to its starting condition and the process is ready to repeat."

We note here that the structure of a Petri net is a directed bipartitle graph (Deo, 1973), consisting of the two types of vertices called places (P's) and transitions (T's). In order to simulate the dynamic behavior of a petri net, each place is marked (assigned with a nonnegative number of tokens). We may think of tokens as representing data itmes or as holding some conditions represented by places. The initial distribution of tokens on places may be regarded as the initial condition, and is called the initial marking or state. A Petri net executes by firing transitions. A transition is said to be firable (or enabled) if each input place of the transition is marked with at least one token. A firable transition may be chosen to fire. The firing of a transition consists of removing one token from each of its input places, and adding one token to each of its output places. We may think of a firing as an event which may take place if certain conditions are satisfied. Each firing will cause the old conditions to cease and new conditions to hold, and the total number of tokens in a Petri net may change after each firing. Note that it is not necessary to fire all firable transitions, although only the firing of a firable transition is legal.

APPENDIX B

MAINTENANCE TASK SELECTION

Appendix B

Maintenance Task Selection

The criteria established for system and subsystem selection are those expressed as follows:

(1) Candidate systems shall be characteristic of current and future maintainability requirements.

(2) Candidate subsystems shall manifest event driven activities involving concurrent and coordinated maintainer/operator participation. Participation shall include recognition and detection of performance characteristics and require a combination of skill, rule, and knowledge based actions.

(3) Candidate system performance shall impact platform mission performance.

(4) Operating procedure requirements for candidate systems and subsystems shall be sufficiently complex to involve the human factor problems of inappropriate task assignments or task loading and the effects of inadequate knowledge.

(5) The maintainability procedures shall permit a diversity of outcomes with optimal and suboptimal results. Procedures shall be sufficiently complex to permit operator caused equipment failure.

(6) Candidate systems and subsystems shall be adaptable to automation aids for event and activity interaction between the system and the operator.

Discussions with Navy Personnel and a review of ONR-NADC activities and responsibilities in relation to the selection criteria has resulted in one prime candidate system: the LM2500 Propulsion Gas Turbine module as configured for the DD963 class of ship. Candidate subsysems include the Gas Turbine Module (GTM) fuel oil system and the lubrication system. The discussion of selection rationale follows the criteria format established in the paragraph above.

(1) The LM2500 Propulsion Gas Turbine module (GTM) can be found on three classes of naval combatants;

(a) Spruance (DD963) class,
(b) Oliver Hazard Perry (FFG 7) class,
(c) Pegasus (PHM1) class.

Future ship classes to use the GTM for main propulsion will be the Ticonderoga (CG 47) class currently authorized for 21 ships through FY 1986 and an undetermined number of undesignated FFX and DDGX vessels.

By 1988, five years hence, it is reasonable to project that of all surface combatants (CG, DDG, DD and FF), 48 percent will be GTM powered and that 92 percent all of that group which are 15 years old or newer will be GTM powered. Of all GTM powered tonnage, 66 percent will be DD 963 power plant configured.

In light of the above, the DD 963 GTM is preeminently characteristic of both current and future maintainability requirements.

(2) The GTM is the prime power source for propulsion. The DD963 propulsion system requires 4 GTM's as shown in Figure B-1. The GTM's power each of the ship's two propulsion shafts as shown in Figure B-2. Failure of a gas turbine and any of its major subsystems results in a direct loss of propulsion horsepower capacity.

(3) Supporting the operation of the gas turbine are two major subsystems. The lubrication system and the fuel oil system are both integral subsystems of the gas turbine, and function continuously during power plant operation.

(a) Background: The GTM is a variant General Electric TF39 and CF6-6 engine which power the Lockheed, USAF/C5A and the McDonnell Douglas DC-10 aircrafts. The engine is composed on an axial gas generator which contains a sixteen stage compressor, a combustor section and a two stage drive turbine coupled to the Main Reduction Gear Assembly. Figure B-3 shows the gas turbine in its shipping frame and Figure B-4 shows the gas generator and power turbine section of the gas turbine. The two sections assemble at the bolt rings shown by the arrows.

(b) Lubrication System: The GTM is supported by a lubrication system which is isolated from the ship's main lubrication system. Unique lubricants required for the high temperature of operation necessitate this arrangement. One Lube Storage and Conditioning Assembly (LSCA) supports every two GTM's as shown in Figure B-1.

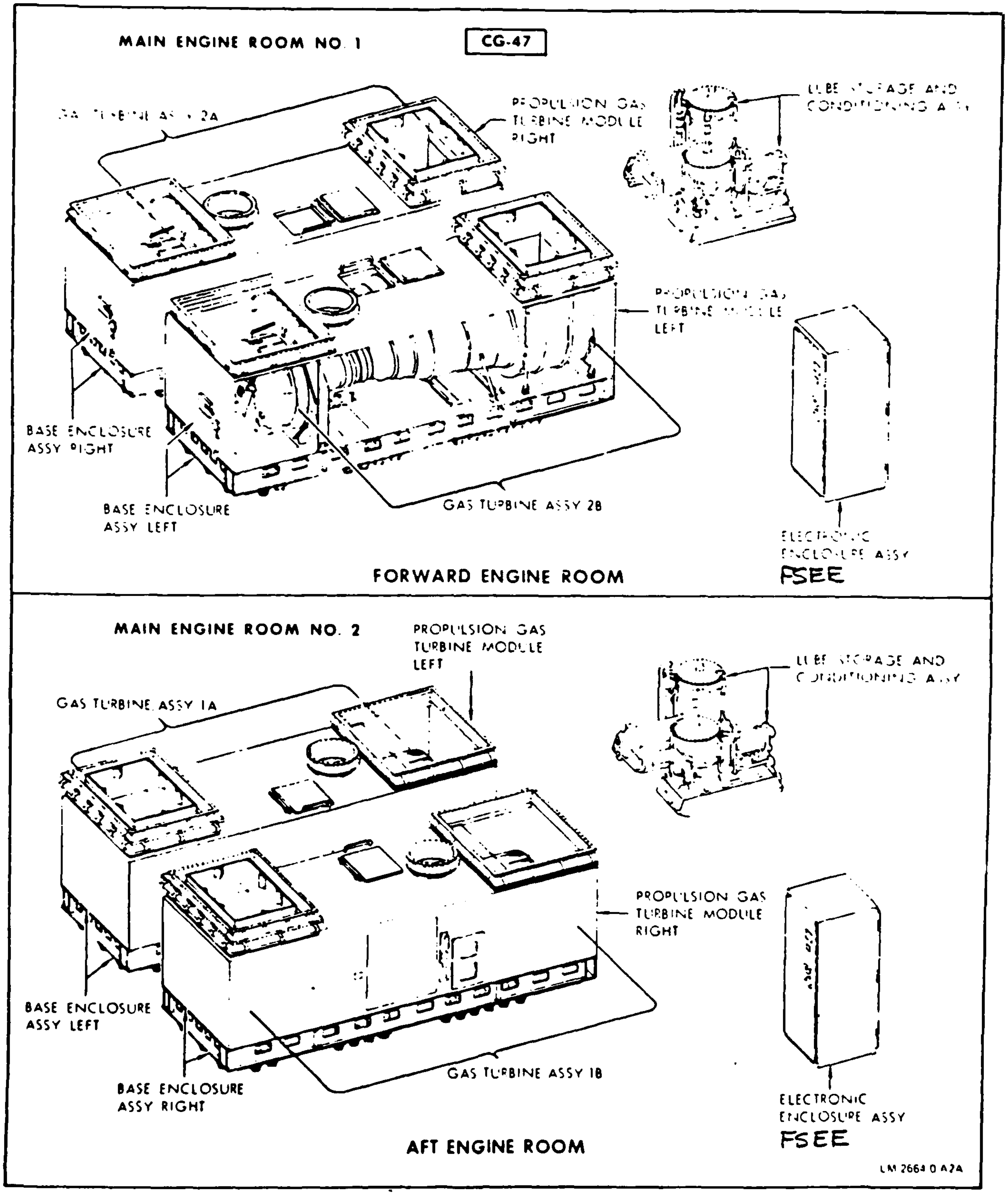

FIGURE B-1.
GAS TURBINE MODULES (GTM) FOR THE
TICONDEROGA CLASS (CG47) OF SHIP

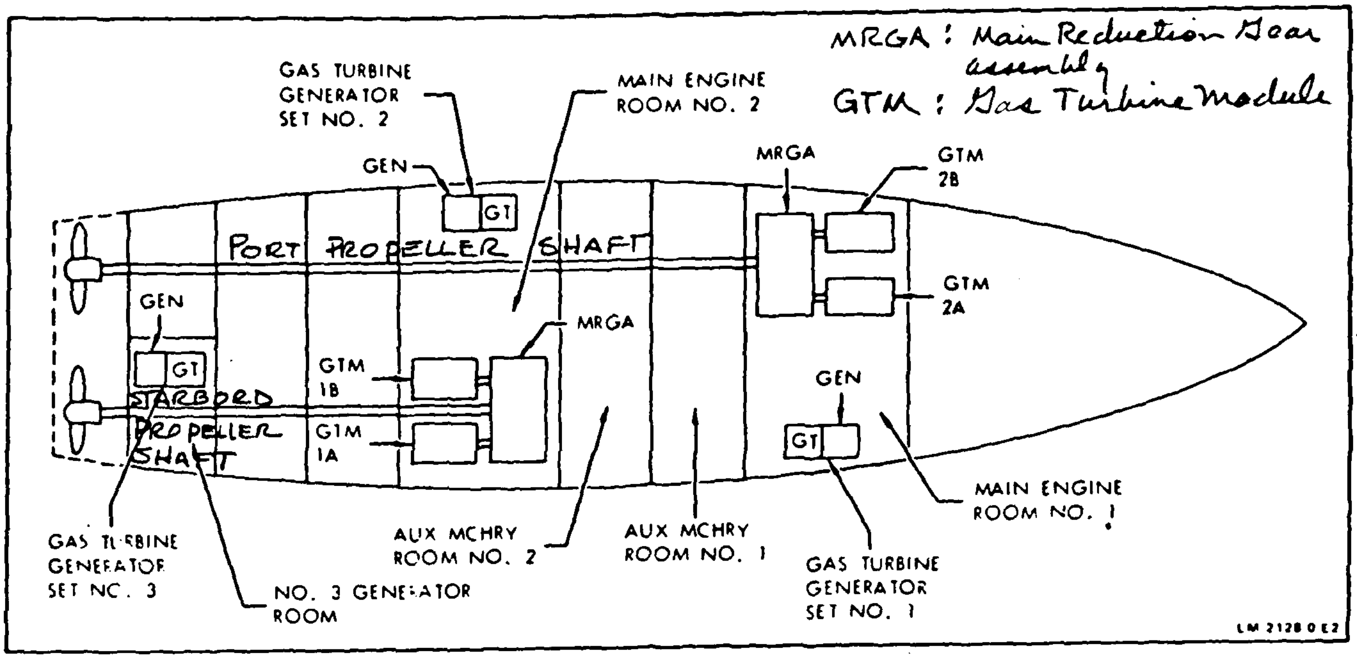

FIGURE B-2A.
DISTRIBUTION OF PROPULSION EQUIPMENT

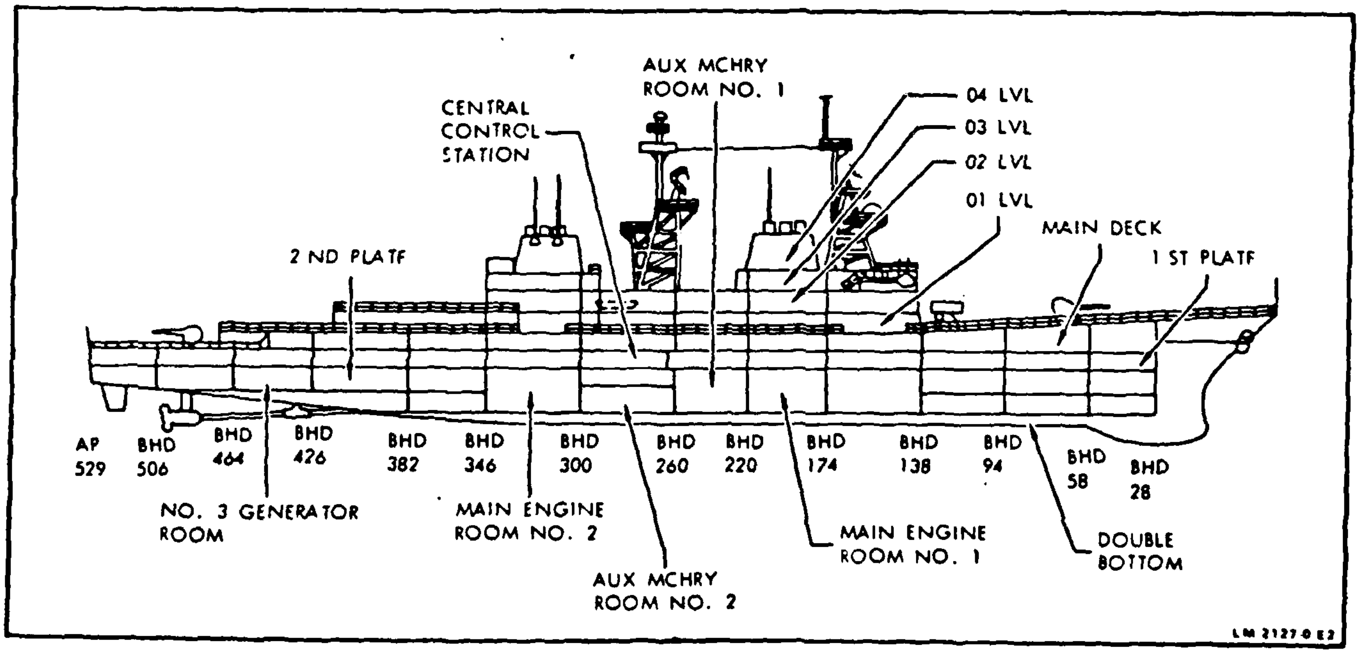

FIGURE B-2B.
SPACE LOCATIONS WITHIN THE DD963/CG47 HULL CONFIGURATION

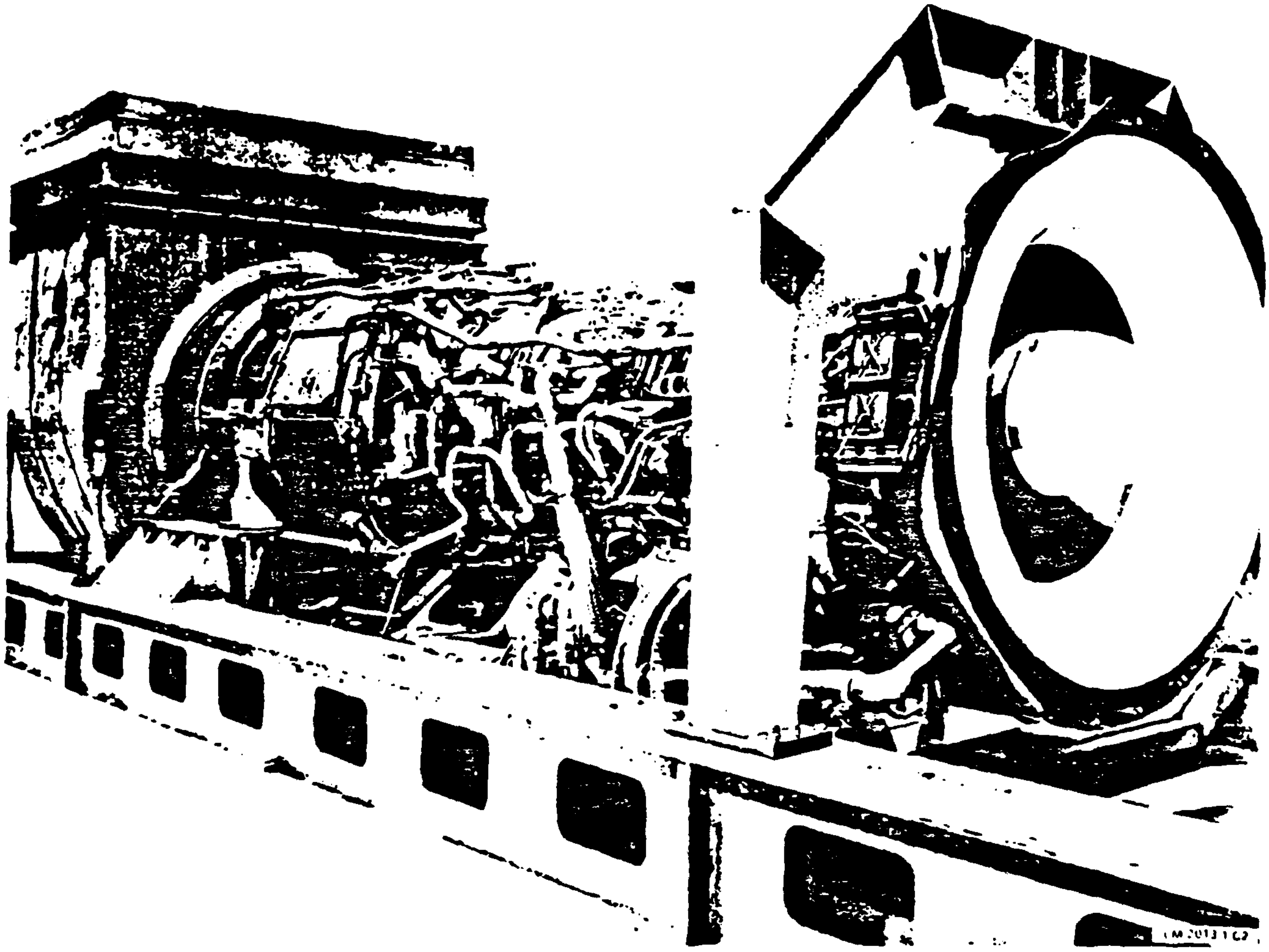

FIGURE B-3.
GAS TURBINE ENGINE OUT OF ITS ENCLOSURE

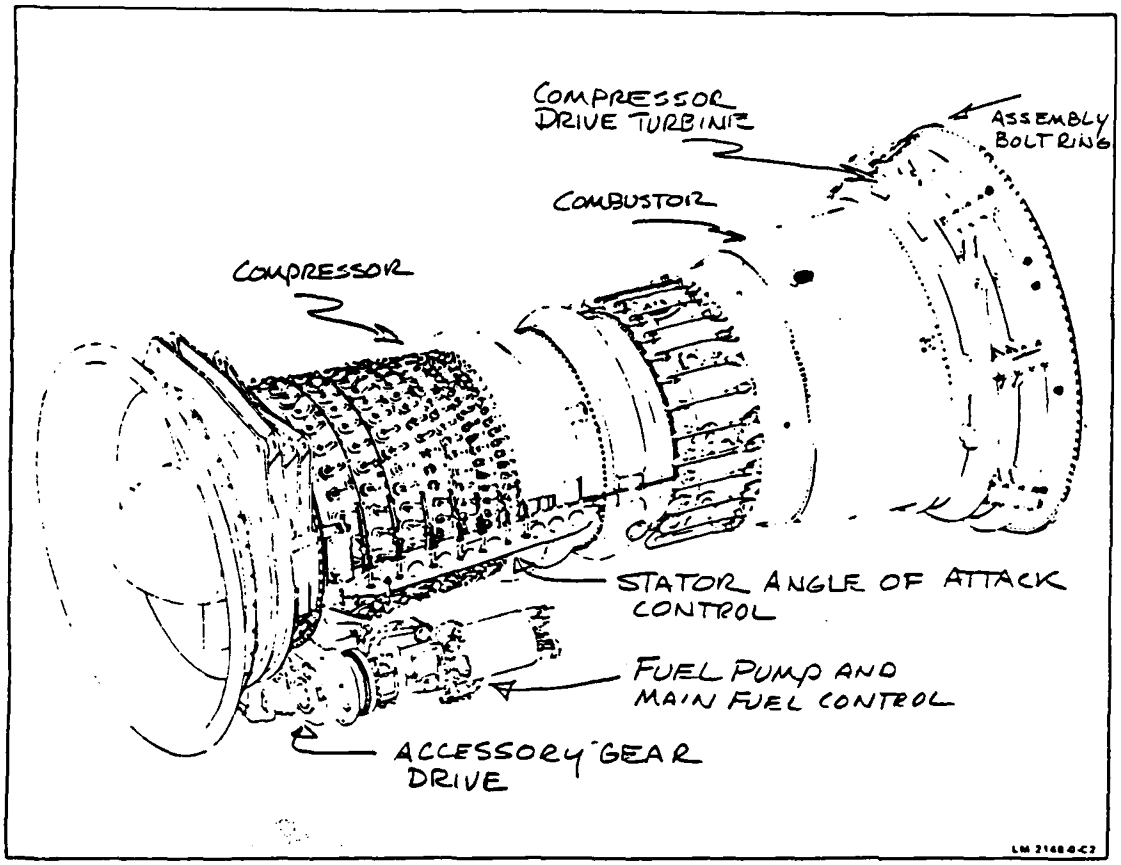

FIGURE B-4A.
GAS GENERATOR

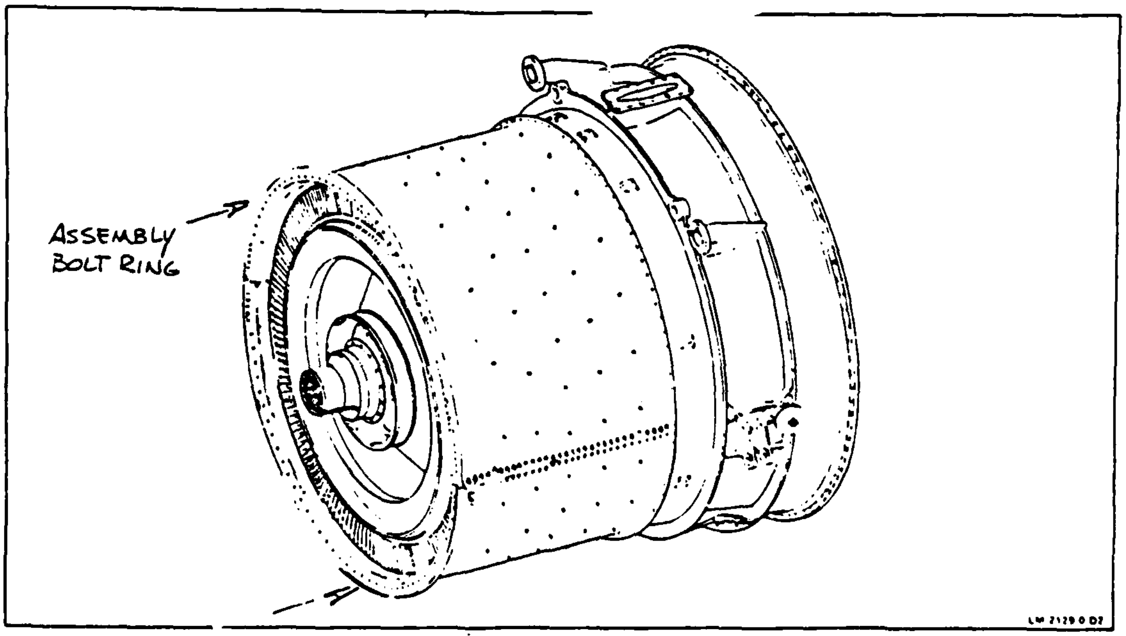

FIGURE B-4B.
POWER TURBINE

The portions of the gas turbine which require lubrication and schematic diagram of the system are shown in Figure B-5. The lube pump which pressurizes oil flow to the bearings, and the scavenge pump which extracts oil from the bearing sumps, and the accessory gear drive are mounted on the accessory gear drive. The LSCA cools the oil via a heat exchanger which uses the ships main lube oil as a collant.

The lubrication system, however important to system operation, provides very few opportunities for operator participation beyond monitoring temperatures pressures and fluid level. System design provides for a direct pressure and flow relationship to the gas generator speed. The system exhibits no operational dynamics and requires few knowledge based actions on the part of the operator.

(c) Fuel System: The fuel system of the GTM performs multiple functions in maintaining control of the gas generator's operation. The primary cause of engine shutdown is compressor stall, which results in a "frame out," an interruption of air flow to the combustor which results in a loss of combustion. Seventy percent compressor stall at various speeds during the gas generator's phases can be fixed by adjusting the compressor station blades (inlet through stage six). This adjustment is referred to as "varying the angle of attack," and is done for the same reason that an aircraft must balance its speed and angle of attack to prevent wing lift stall.

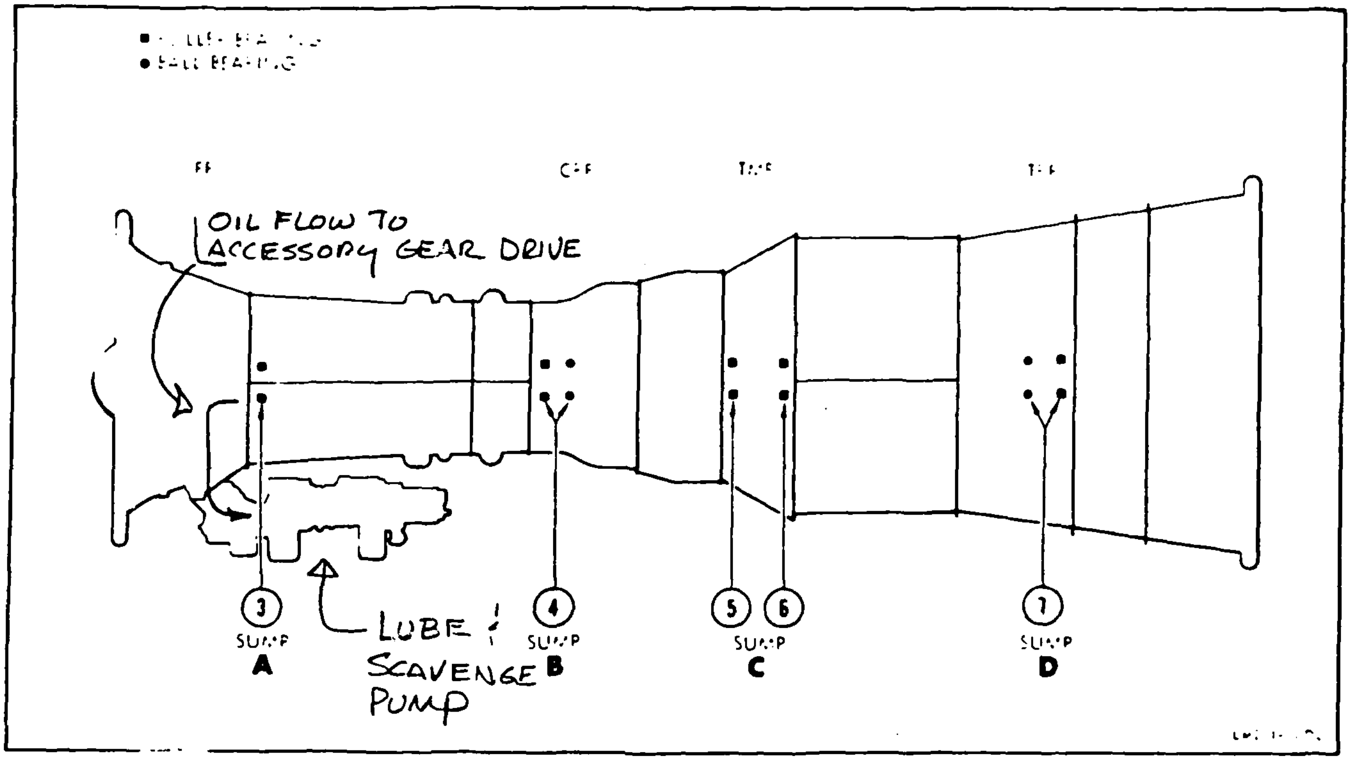

FIGURE B-5A.
POINTS OF LUBRICATION

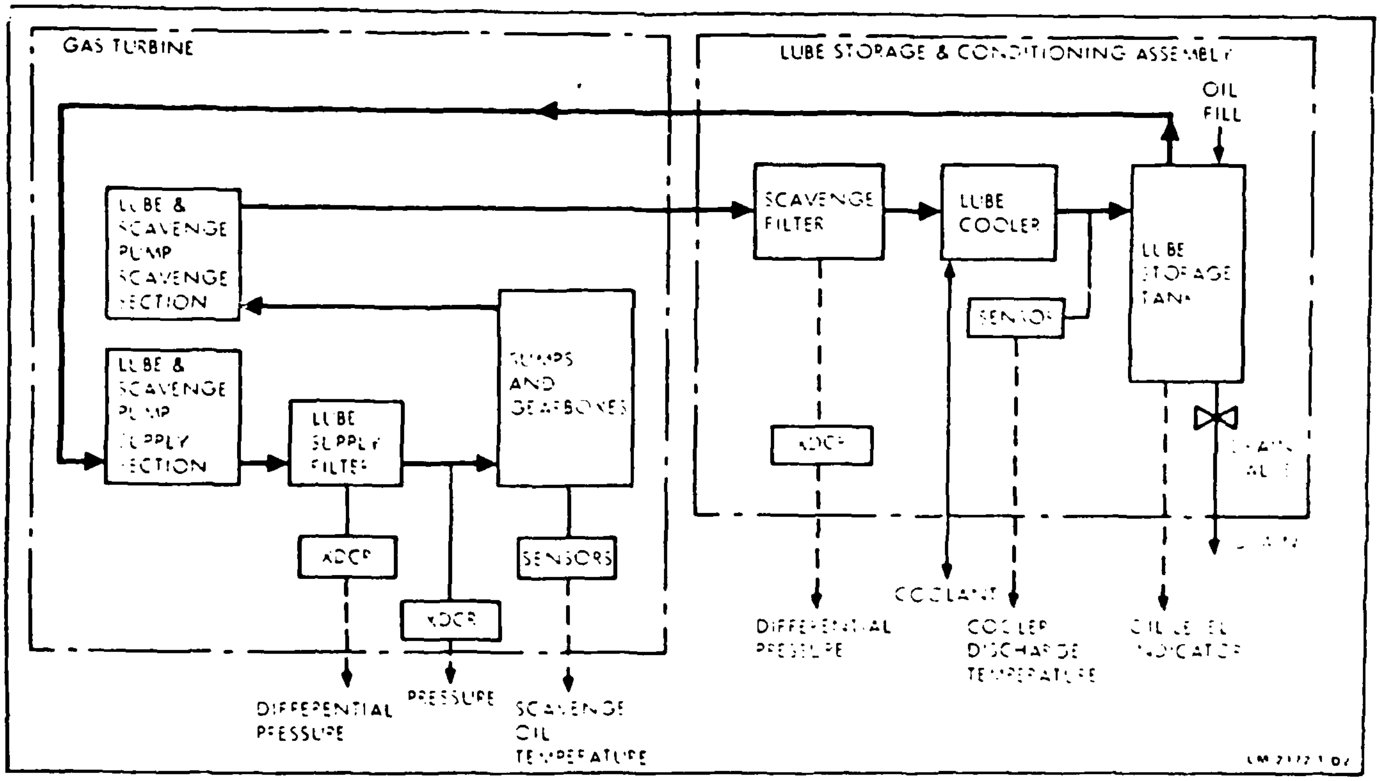

FIGURE B-5B.
LUBRICATION FUNCTIONAL DIAGRAM

AD-A151 302 DESIGN FOR MAINTAINABILITY WITH MODIFIED PETRI NETS (MPNS): SHIPBOARD PRO..(U) PERCEPTRONICS INC WOODLAND HILLS CA A M MADNI ET AL. NOV 84 PFTR-1125-84-11 2/2

UNCLASSIFIED N00014-82-C-0683 F/G 5/9 NL

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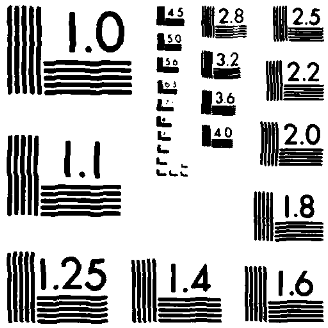

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963-A

The angle of attack must be adjusted continuously throughout the operating speed and power range. In conjunction with fuel flow to the combustor, the angle of attack controls the rate of acceleration and deacceleration and permits a degree of engine control flexibility that the gas generator would not otherwise have.

Fuel pressure is ported to the hydraulic control cylinder which controls the variable stator vane actuators. Establishing correct flow rates, pressures and receiving feedback signals is the function of the main fuel control. Figure B-6 shows the fuel system flow, sensors, and feedback elements of the fuel control system.

The fuel system is an integral portion of the gas turbine electronic power control system. It should be remembered that the GTM is comprised of the gas generator and an independent power turbine. The fuel system therefore functions as part of the overall system to control output shaft torque and rotational speed. Figure B-7 describes in general the functions of the Free Standing Electronics Enclosure (FSEE), which continuously computes fuel adjustments based upon power command and gas turbine condition sensor signals. The FSEE is shown in Figure B-1.

The fuel system is an excellent candidate for subsystem selection due the variety of functions performed. It satisfies the criteria established earlier due to the following:

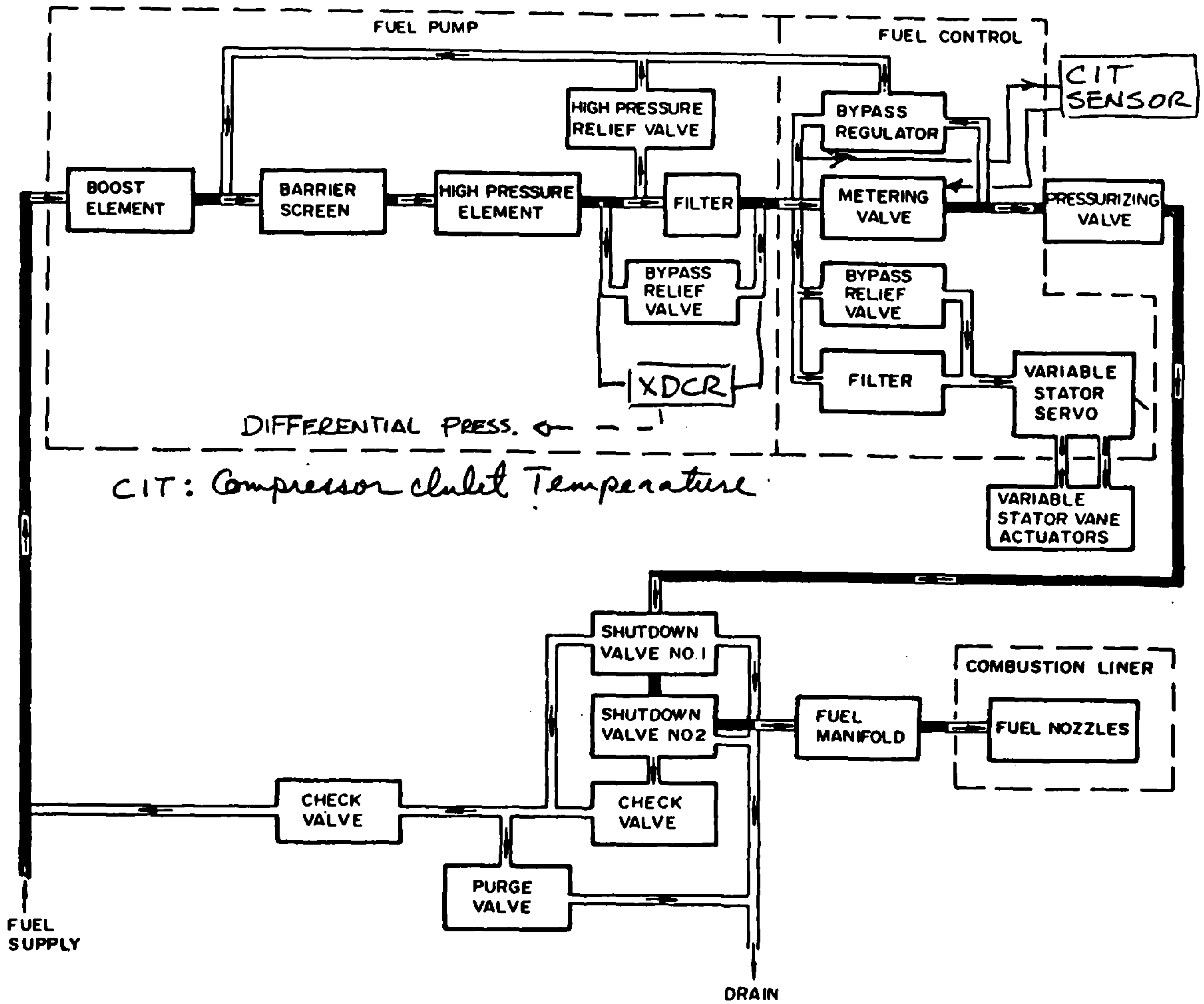

FIGURE B-6.
FUEL SYSTEM FUNCTIONAL DIAGRAM

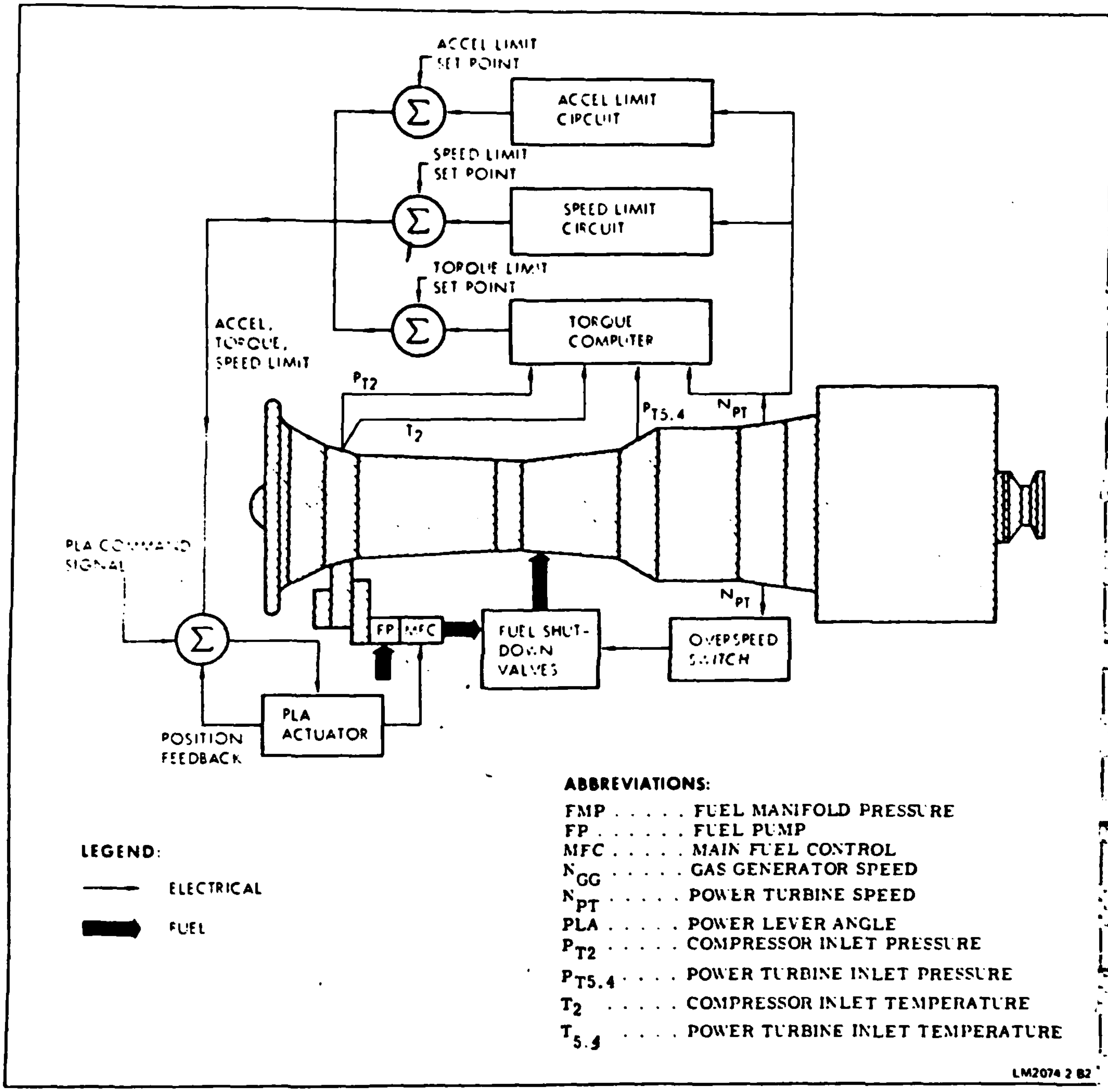

FIGURE B-7.
GAS TURBINE ELECTRONIC POWER CONTROL

1) provides continuous dynamic control of the gas generator fuel flow and compressor air flow to maintain proper combustion;

2) functions as a major element in the power turbine output control system with multiple levels of feedback control;

(3) is capable of operating at a suboptimal level such that operator diagnostics are required to identify and correct performance.

(4) The operating system for GTM powered ships of the DD963 class and above provide three levels of automatic control. Since the FSEE is an essential portion of all GTM operation, a manual mode of GTM operation is not an option.

(a) The GTM and the remainder of the propulsion plant can be operated from four locations: the bridge (highest level of abstraction and ship control decision level), the central control station (direct engineering control level but isolated from the propulsion equipment), and the propulsion local operating equipment (PLOE) station (direct GTM control capable of direct man-machine interface for operator recognition and detection). Figure B-2B shows the location within the ship of each location. Figure B-8 shows the overall Engineering Control and Surveillance System (ECSS).

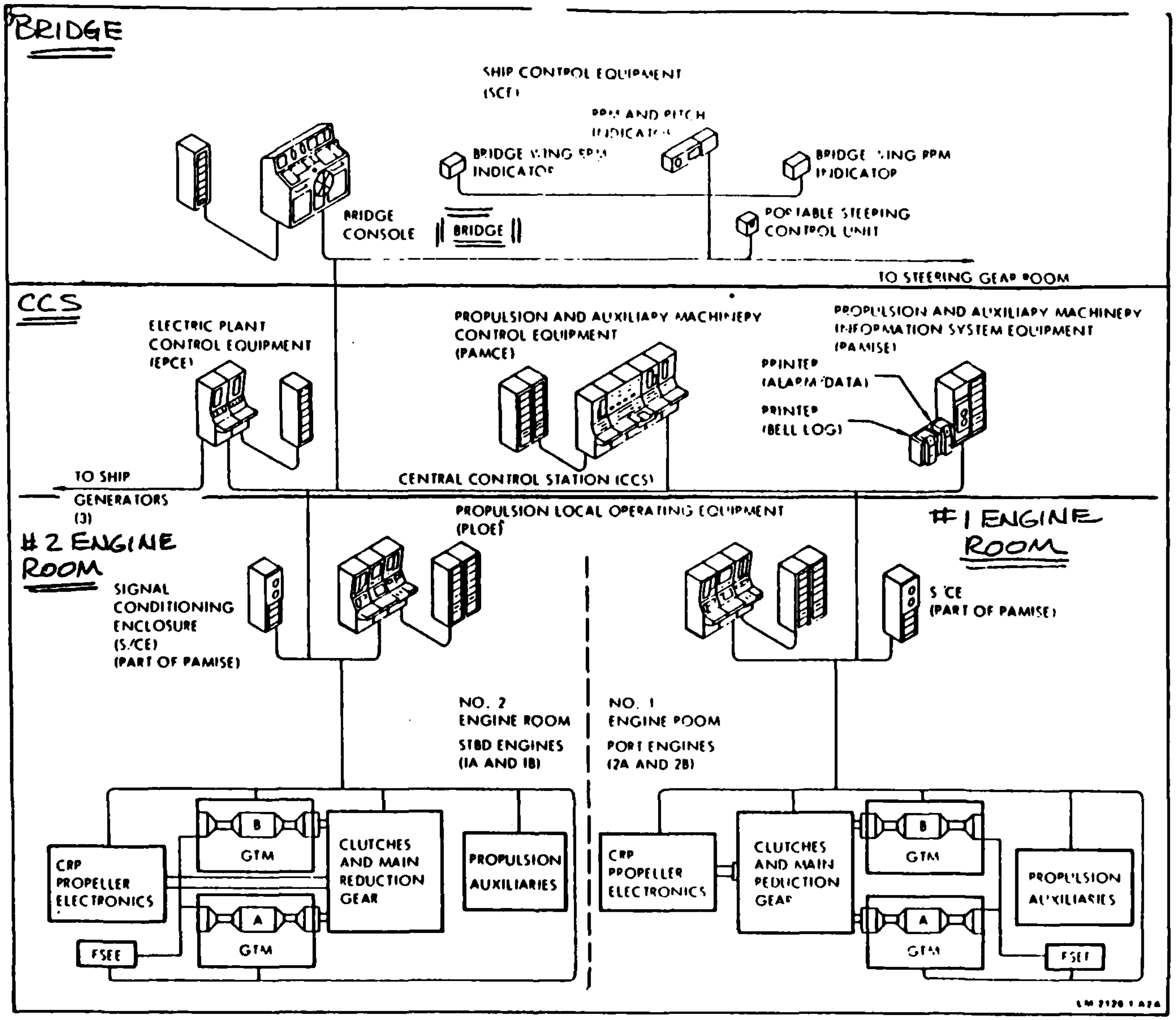

FIGURE B-8.
ENGINEERING CONTROL AND SURVEILLANCE SYSTEM (ECSS)

(b) All three levels of control are continuously manned during operation and have hierarchical operating procedures for propulsion plant control. Figure B-9 displays signal flow during bridge operation of both propulsion plants. Malfunctions or out-of-limits parameters may be observed at both the central control station and the engine rooms via the ECSS equipment installed in each space; however, direct observation is possible only at the GTM. Such a situation becomes critical at the inception of failure of equipment such as the fuel system.

(c) Suboptimal operation of the MFC would likely result in transient stall conditions in the gas generator. Current diagnostic guidelines state that such conditions may only be apparent at the local operating station. The event structure for such a situation would be: (i) bridge has propulsion control with no knowledge of any plant conditions, (ii) central control station has full plant monitoring responsibility and only monitors the bridge's control of propulsion operation, and (iii) the local operator monitors operation of the GTM in conjunction with other engine room equipment and has no function in direct propulsion control.

(d) A variety of task loadings and assignments are possible within the various model of operating procedures. The opportunities for human factor problems exist due to isolated operation of equipment, monitoring of equipment operation with limited sensor display,

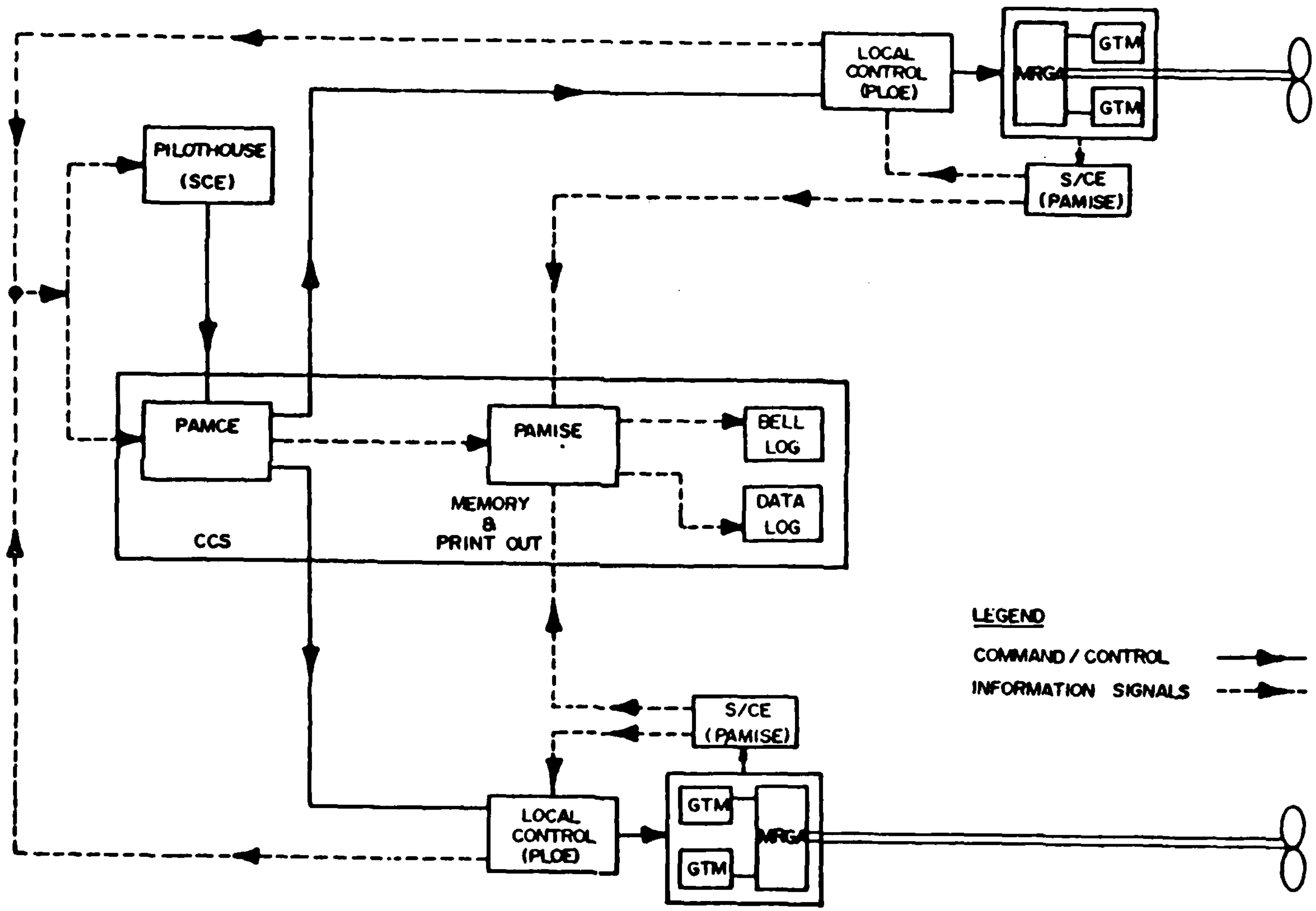

FIGURE B-9.
ECSS CONTROL AND FEEDBACK SIGNAL SYSTEM

responsibility to monitor without authority to control, and a three level communication network consisting of control console information and verbal information.

(5) Current diagnostic guides are definite regarding many malfunctions of the GTM, and have straightforward decision tree checklists to follow in the event of out-of limits operation. In those cases involving gas generator stall, the recommended actions are more general and require maintainer knowledge based actions. It is significant to note that at the most likely time of malfunction the operator will be two levels of abstraction from the maintainer.

The above conditions lead to complex event structures involving communications, changes in equipment control and difficult decisions. Under procedural guides known at this time, this situation could result in unnecessary failure.

(6) The GTM as discussed above requires electronic automation for its immediate operation and control. The ECSS as shown in Figure B-8 and B-9 is a complex electronic display and control system. Given the level of automation to which the propulsion plant is already designed, it is considered very likely that further automation could be developed to aid in the operation of the system.

Both the LM2500 lube oil and fuel system of the propulsion plant GTM and ECSS as it is configured on the DD963 class vessel are considered to be satisfactory candidates for the subject study. However, the lube oil system is more complicated and contributes to frequent maintenance problems. The problems associated with the lube oil system, especially the main reduction gear lube oil system, are time-stressed, and cause greater damage to the gas turbine plant, which often leads to total disruption of the ship's propulsion function. Consequently, since the lube oil system poses a more severe maintainability problem to the Navy maintenance personnel, it was selected for analysis of human-related maintainability problems.

APPENDIX C

HUMAN BEHAVIOR CLASSIFICATION

Appendix C

Human Behavior Classification

Some basic ideas about human behavior and human thinking are inevitably necessary when automation is considered. One might think of activities like teaching, training, task allocation between man and machine, information presentation to operators, and so on. When designing automation, all too often little regard is given to human behavior and human thinking. This leads to negative benefits. Even a relatively simple model of human behavior is better than none at all. To this end, a convenient means of looking at human behavior is provided by Rasmussen (1978). Rasmussen distinguishes three different categories of human behavior in controlling or supervising tasks: skill-based, rule-based and knowledge-based behavior. These categories are depicted in Figure C-1, which shows a scheme of the major ways in which information from sensory inputs are converted into actions. The characteristics of each of these behavior categories along with examples of each are given in Table C-1.

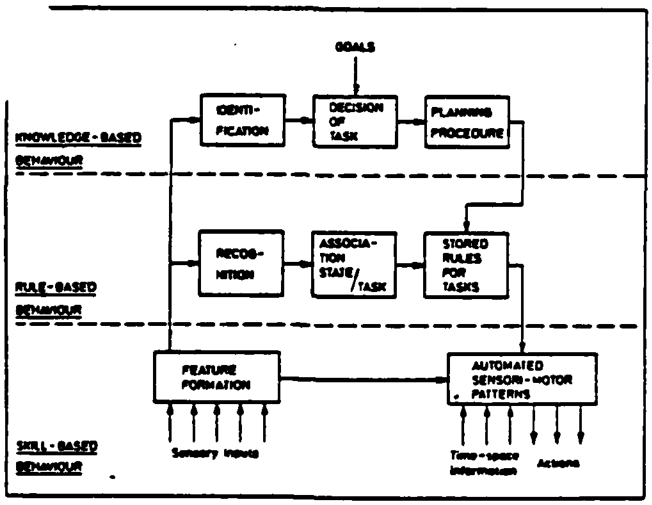

Figure C-1. Rasmussen's Behavior Taxonomy

TABLE C-1

OPERATOR BEHAVIORS IN ENGINE ROOM TRANSIENT MANAGEMENT

BEHAVIOR	CHARACTERISTICS	EXAMPLES
Skill-Based	• little or no conscious attention and effort • automated or nearly automated actions	using tools, reading gauges
Rule-Based	• more mental effort • pre-specified but not necessarily formalized actions • rules can be empirically derived (trial & error), formed by causal reasoning or prescribed as formal work instructions • recognizable situations/states can be directly mapped/associated with specific actions • template.matching	fault correction
Knowledge-Based	• highest mental effort • problem solving • requires conscious attention • higher-level thinking using fundamental principles and knowledge to deduce and/or infer which actions to take	fault diagnosis

Skill-Based Behavior. The lowest level, skill-based behavior, is the area of automated or nearly automated actions like walking, bicycle riding, and so on. They require little or no conscious attention and effort. For an experienced operator, using tools and reading gauges falls into this category.

Rule-Based Behavior. At the middle level, the level of rule-based behavior, more mental effort is required. Whereas skill-based behavior is typical for repetitive, frequently performed tasks (e.g.,simple assembly-line actions) the rule based behavior is typical for less frequent tasks in a familiar work environment (e.g., complex assembly-line actions and emergency procedures in a power plant). Rule-based behavior concerns pre-specified, but not necessarily formalized, actions. The rules underlying the behavior can be prescribed as formal work instructions. Recognizable situations or states can be directly mapped on, or associated with specific actions. In rule-based behavior, both situation and connected action are conscious; the mapping and the associational rule are not.

Knowledge-Based Behavior. The third, and highest level of behavior in terms of mental effort on the operator's part, is the knowledge-based level. Quoting Rasmussen (1980): "This is the level of intelligent problem solving which should be the prominent reason for the presence of human operators in an automatic plant. Behavior in this domain is activated in response to unfamiliar demands from the system. The structure of the activity is an evaluation of the situation and planning of a proper sequence of actions to pursue the goal. The activity depends upon fundamental knowledge of the processes, functions and anatomical structure of the system." Knowledge-based behavior involves high-level thinking, typically using fundamental principles and knowledge to deduce and/or infer which actions should be taken. In this behavior-area no pre-specified guidelines normally exist. All the stages depicted in Figure C-1 at the knowledge-based level, have to be given conscious attention.

This three-level behavior classification provides a convenient framework for initially analyzing control room operator tasks.

APPENDIX D

SAMPLE OUTPUT

TIME 0
P1
Monitor MRG pressure gauge.
TIME 2
T1
Engine room reports major lube oil leak in MRG lube oil system.
P2
Evaluate magnitude and location of leak.
TIME 7
T7
Post fork leak.
P8
Inform engine room of EOCC.
P11
EOW orders engineering spaces manned.
TIME 10
T12
PACC operator reports to EOW, "No. i lube oil service system secured. No. i GTM stopped. It is at CCS. No. i shaft stopped with shaft brake on."
P8
Inform engine room of EOCC.
P12
EOW reports to OOD, "Major lube oil leak in no. i engineroom. No. i GTM is stopped. ITC is at CCS. No. i shaft is stopped with shaft brake on. Maximum speed available is i knots."
TIME 21
T13
EPCC operator reports to EOW, "No. i GTG is stopped. No. i GTG is online and in parallel with no. i GTG."
P8
Inform engine room of EOCC.
P13
Monitor.
TIME 22
T14
Engineering spaces report manned.
P8
Inform engine room of EOCC.
P14
Monitor.
TIME 23
T15
No. i engineroom reports to EOW, "Main reduction gear lube oil service system leak is isolated."
P8
Inform engine room of EOCC.
P15
Monitor.
TIME 24
T16
PACC operator reports to EOW, "Bleed air secured from no. i GTM and isolated from no. 3 GTG."
P8
Inform engine room of EOCC.
P16
Monitor.
TIME 25
T17
Unaffected engineroom reports to EOW, "Bleed air secured from no. i GTG."

P8
Inform engine room of EOCC.
P17
Monitor.
TIME 26
T18
No. 1 engineroom reports to EOW, "Lube oil flushed into bilges, covering with AFFF."
P8
Inform engine room of EOCC.
P18
EOW reports to OOD, "Major lube oil leak in no. 1 engineroom is isolated. Lube oil in no. 1 engineroom is flushed into bilges and covered with AFFF." EOW requests permission from OOD to remove fire hazards (in accordance with current environmental protection requirements)."
TIME 41
T19
OOD grants permission.
P8
Inform engine room of EOCC.
P19
EOW orders no. 1 engineroom to remove fire hazards (in accordance with current environmental protection requirements).
TIME 51
T20
No. 1 engineroom reports to EOW, "Fire hazards removed."
P8
Inform engine room of EOCC.
P20
EOW reports to OOD, "Fire hazards removed from no. 1 engineroom." EOW orders no. 1 engineroom to investigate for the cause of the casualty using approved maintenance procedures and technical manuals.
TIME 62
T21
No. 1 engineroom reports to EOW cause of the casualty and estimated time to repair.
P8
Inform engine room of EOCC.
P21
EOW reports to OOD the cause of the casualty and estimated time to repair.
TIME 73
T22
Casualty cannot be restored in a reasonable amount of time.
P8
Inform engine room of EOCC.
P22
EOW requests permission from OOD to stop the ship to lock no. 1 shaft.
TIME 78
T23
OOD grants permission to stop the ship.
P8
Inform engine room of EOCC.
P23
EOW orders PACC operator to place the unaffected shaft ITC lever at 'STOP' and maintain zero thrust.
TIME 93
T24
When the SHIP SPEED indicator is at "0" knots, PACC operator reports to EOW, "ITC lever is at 'STOP'. Maintaining zero thrust on no. 1 shaft."
P8
Inform engine room of EOCC.
P24
EOW orders PACC operator to release the shaft brake on the affected shaft.
TIME 98
T25
PACC operator reports to EOW, "No. 1 shaft brake is released."

P8
Inform engine room of EOCC.
P25
EOW locks no. 1 shaft.
TIME 101
T32
Shutdown complete.
P8
Inform engine room of EOCC.
P32
Repairs proceeding.
TIME 126
T35
Dummy complete.
T8
Engine room informed and repairs complete.
P9
Evaluate/restore normal operation.
TIME 128
T9
Normal operation restored.
P1
Monitor MRG pressure gauge.

TIME	INST WORKLOAD	CUM WORKLOAD
0	9.999999e-02	0.000000e+00
1	9.999999e-02	9.999999e-02
2	1.700000e+00	2.000000e-01
3	1.633033e+00	1.900000e+00
4	1.570550e+00	3.533033e+00
5	1.512252e+00	5.103583e+00
6	1.457858e+00	6.615835e+00
7	1.307107e+00	8.073693e+00
8	1.197864e+00	9.380799e+00
9	1.104560e+00	1.057866e+01
10	1.424349e+00	1.168322e+01
11	1.293052e+00	1.310757e+01
12	1.183482e+00	1.440062e+01
13	1.091516e+00	1.558410e+01
14	1.013858e+00	1.667562e+01
15	9.478672e-01	1.768948e+01
16	8.914291e-01	1.863734e+01
17	8.428446e-01	1.952877e+01
18	8.007475e-01	2.037161e+01
19	7.640360e-01	2.117236e+01
20	7.318202e-01	2.193640e+01
21	7.033785e-01	2.266821e+01
22	8.162350e-01	2.337159e+01
23	8.859904e-01	2.418783e+01
24	9.267764e-01	2.507382e+01
25	9.483125e-01	2.600059e+01
26	1.257252e+00	2.694890e+01
27	1.058123e+00	2.820615e+01
28	9.125631e-01	2.926428e+01
29	8.054643e-01	3.017684e+01
30	7.260496e-01	3.098230e+01
31	6.666228e-01	3.170835e+01
32	6.216803e-01	3.237497e+01
33	5.872797e-01	3.299665e+01
34	5.605917e-01	3.358393e+01
35	5.395814e-01	3.414452e+01
36	5.227812e-01	3.468410e+01
37	5.091296e-01	3.520687e+01
38	4.978560e-01	3.571600e+01
39	4.883984e-01	3.621386e+01
40	4.803452e-01	3.670225e+01

41	5.733929e-01	3.718259e+01
42	5.173163e-01	3.775599e+01
43	4.869471e-01	3.827330e+01
44	4.696581e-01	3.876025e+01
45	4.591024e-01	3.922990e+01
46	4.520800e-01	3.968900e+01
47	4.469702e-01	4.014108e+01
48	4.429455e-01	4.058805e+01
49	4.395779e-01	4.103099e+01
50	4.366421e-01	4.147057e+01
51	5.340151e-01	4.190721e+01
52	4.816274e-01	4.244122e+01
53	4.544365e-01	4.292285e+01
54	4.399150e-01	4.337728e+01
55	4.317932e-01	4.381720e+01
56	4.269314e-01	4.424899e+01
57	4.237551e-01	4.467592e+01
58	4.214728e-01	4.509967e+01
59	4.196852e-01	4.552114e+01
60	4.181891e-01	4.594082e+01
61	4.168797e-01	4.635901e+01
62	7.157018e-01	4.677589e+01
63	6.527352e-01	4.749158e+01
64	6.026200e-01	4.814432e+01
65	5.627111e-01	4.874694e+01
66	5.309104e-01	4.930965e+01
67	5.055526e-01	4.984055e+01
68	4.853161e-01	5.034610e+01
69	4.691515e-01	5.083142e+01
70	4.562256e-01	5.130057e+01
71	4.458766e-01	5.175679e+01
72	4.375789e-01	5.220266e+01
73	8.309149e-01	5.264024e+01
74	7.608281e-01	5.347115e+01
75	7.001580e-01	5.423198e+01
76	6.476105e-01	5.493214e+01
77	6.020746e-01	5.557975e+01
78	6.625959e-01	5.618182e+01
79	5.783531e-01	5.684441e+01
80	5.236395e-01	5.742276e+01
81	4.853458e-01	5.794640e+01
82	4.566967e-01	5.843174e+01
83	4.341136e-01	5.888844e+01
84	4.156423e-01	5.932255e+01
85	4.001630e-01	5.973819e+01
86	3.869922e-01	6.013836e+01
87	3.756813e-01	6.052534e+01
88	3.659131e-01	6.090102e+01
89	3.574488e-01	6.126693e+01
90	3.500992e-01	6.162438e+01
91	3.437093e-01	6.197448e+01
92	3.381490e-01	6.231819e+01
93	4.333079e-01	6.265633e+01
94	3.790911e-01	6.308964e+01
95	3.504167e-01	6.346873e+01
96	3.347141e-01	6.381915e+01
97	3.256719e-01	6.415385e+01
98	4.201119e-01	6.447952e+01
99	3.664253e-01	6.489963e+01
100	3.387907e-01	6.526605e+01
101	4.242825e-01	6.560484e+01
102	3.664251e-01	6.602911e+01
103	3.369693e-01	6.639554e+01
104	3.217809e-01	6.673251e+01
105	3.137842e-01	6.705428e+01
106	3.094338e-01	6.736806e+01

107	3.069507e-01	6.767750e+01
108	3.054397e-01	6.798444e+01
109	3.044485e-01	6.828988e+01
110	3.037463e-01	6.859432e+01
111	3.032143e-01	6.889806e+01
112	3.027898e-01	6.920127e+01
113	3.024385e-01	6.950406e+01
114	3.021409e-01	6.980650e+01
115	3.018851e-01	7.010863e+01
116	3.016632e-01	7.041051e+01
117	3.014697e-01	7.071217e+01
118	3.013003e-01	7.101364e+01
119	3.011517e-01	7.131494e+01
120	3.010212e-01	7.161609e+01
121	3.009064e-01	7.191711e+01
122	3.008053e-01	7.221801e+01
123	3.007163e-01	7.251881e+01
124	3.006378e-01	7.281953e+01
125	3.005685e-01	7.312016e+01
126	8.005072e-01	7.342073e+01
127	7.504531e-01	7.422124e+01
128	2.254053e-01	7.497169e+01

APPENDIX E

EXISTING U.S. NAVY MAINTENANCE DATA SOURCES

Appendix E

Existing U.S. Navy Maintenance Data Sources

To improve design for maintainability and to verify the proposed approach it is necessary to have access to a systematic collection of pertinent information about maintenance tasks, the equipment to which those tasks relate, and the personnel performing them. Relevant maintainability information includes the following:

(1) The classes of maintenance tasks that apply across types of Navy Gas Turbine propulsion equipment and the specific types of equipment to which they apply.
(2) The relative importance of the classes of maintenance tasks across all types of gas turbine related equipment.
(3) The difficulty of performing each class of maintenance task across types of equipment.
(4) The types of maintainability problems that affect each class of maintenance tasks across all types of equipment and for each type of equipment.
(5) The severity of each maintainability problem across classes of maintenance tasks and types of equipment and for each class of maintenance task and specific type of equipment.

The above information is currently available in part in U.S. Navy maintenance data bases. In addition, other types of information, which could be transformed into the required types, are available in these data bases. This section consists of a matrix of U.S. Navy maintenance data sources by their contents, and the utility of their contents for this program; plus a general discussion of the nature of the more significant data sources that have been identified.

1. Overview of Navy Maintenance Data Sources

The surface and subsurface U.S. Navy has one major maintenance data management system--the Maintenance Data System (MDS) module of the Ship's Maintenance and Material Management (3M) System. MDS is used to manipulate and manage a series of primary data sources. In addition, the surface and subsurface Navy has a group of non-MDS primary data sources. Navy air has one major data management system that may be pertinent to the question of maintainability--the Aircraft Deficiency Storage, Tracking and Retrieval System (ADSTARS). The primary data sources that make up MDS, as well as the non-MDS sources--are of importance because of the possible utility of their contents for the maintainability design program. ADSTARS' importance is based on the potential similarity of the maintainability problems to ship problems.

This section will describe the most potentially useful data sources, indicate their differences and similarities, estimate their utility for this program, and specify where they can be accessed.

2. MDS Data Sources

MDS data sources that have significant utility for this program are 4790/2 series.

2.1 OPNAV 4790/2K. OPNAV 4790/2K is the primary data source of MDS. It is a standard form that is filled out when a maintenance action is performed. It includes the following information:

(1) Identification of the equipment that was maintained.
(2) The class of maintenance job(s) performed on the equipment.
(3) The nature of the equipment failure.
(4) The reason for the equipment failure.

(5) Any alteration of the equipment that took place.

(6) The priority of the maintenance action.

(7) The rating (E1, E2, etc.) of the maintenance personnel.

(8) The time required to troubleshoot the problem.

(9) The number of man hours required to perform the maintenance action.

(10) The real time required to perform the maintenance action.

(11) The problems encountered in performing maintenance.

(12) The hazards encountered in performing maintenance.

The information contained in the various OPNAV 4790/2K's should be extremely useful for this program. It provides the classes of maintenance jobs and types of equipment to which those jobs apply. Depending upon the distinction of jobs versus tasks, this should greatly aid the process of determining the classes of maintenance tasks or activities that apply across types of Navy equipment and the specific types of equipment to which they apply. The priorities of various maintenance actions should be equivalent to the relative importance of the classes of maintenance jobs. The required maintenance times, the required number of maintenance personnel, and the ratings of those personnel should provide a basis for determining an estimate of job difficulty. The descriptions of the problems and hazards encountered in maintenance performance may prove useful in defining the maintainability problems that apply to each maintenance job and type of equipment.

There are <u>three principal difficulties</u> in the use of OPNAV 4790/2K:

(1) It is based on maintenance jobs rather than tasks, and they may be at too gross a level for full utility.

(2) Problems and hazards may either be absent, or not translatable into maintainability problems.

(3) There is no check on the accuracy of recorded data.

However, these three difficulties with OPNAV 4790/2K should not prevent this data source from being extraordinarily useful. It is expected that OPNAV 4790/2K should be one of the basic data sources for this program.

2.2 Other Data Sources. Other data sources (Master Job Catalog, Planned Maintenance System Records, OPNAV 4790/2B, 2P, 2F, 2R, and 2Q, Ship Force Work List) may be useful, but are based on reformatting of the same information as those previously described.

3. Non-MDS Data Sources

There are a large number of potentially pertinent data sources that are not part of MDS. There are four categories of non-MDS data sources that have the greatest potential to aid this program by providing maintainability problems specific to pieces of equipment and/or maintenance tasks. These four categories of data sources are:

(1) Equipment Logs and Operating Records.
(2) Inspection and Test Reports.
(3) Summary Maintenance Condition and Readiness Reports.
(4) Safety Hazard Reports.

Other categories of non-MDS data may prove useful, but these four appear to have the highest probability of providing the elusive maintainability problem data. It is unlikely that the non-MDS data sources will provide information, other than maintainability problems, that is not available from the MDS sources.

3.1 Equipment Logs and Operating Records. This category includes a number of data sources. The types of data sources that currently appear to be the most pertinent to this program include:

(1) Engineering Log.
(2) Gas Turbine Module (GTM) Operating Records.
(3) Engine Trend Analysis Record.

These three types of data sources appear to be pertinent to this program, but it will be necessary to examine a reasonable sample of the others to determine if they contain maintainability problems. The accessibility to the data sources may present a problem.

3.2 Inspection and Test Reports. This category includes a minimum of 25 types of data sources. Of these 25, the types of data sources that currently appear to be pertinent to this program are:

(1) Engineering Trial Reports.
(2) Propulsion Examining Board (PEB) Light-Off Examination Reports.
(3) PEB Operating Propulsion Plant Examination Reports.
(4) INSURV Inspection Reports.

These four types of data sources should contain any maintainability problems, dealing with propulsion units, in this category of non-MDS data.

3.3 Summary Maintenance Condition and Readiness Reports. This category includes a minimum of four types of data sources:

(1) Report of Significant Casualties.
(2) Force Status Reporting System (FORSTAT).
(3) Commanding Officer's Narrative Reports.
(4) Department 8 O'Clock Reports.

The above types of data sources may be examined for cross-checking purposes. Particular attention will be given to reports of significant casualties and commanding officer's narrative reports as potential sources of maintainability problem data.

3.4 Safety Hazard Reports. This category currently includes two types of data sources:

(1) Serious Safety Deficiency Reports.
(2) Forces Afloat Accident/Near Accident Reports.

Both of these types of reports deal with significant safety problems and, as such, may describe those safety problems that impact maintenance of equipment.

3.5 Other Non-MDS Data Sources. Other categories of non-MDS data sources exist. At the present time, these other sources appear to be potentially less fruitful than those described. However, they will be sampled to determine if significant information may be found by accessing them.

Table E-1 describes sample non-MDS data sources in context categories. These tables are adapted from the three-volume study entitled "Ship Maintenance Data Sources and Systems: An Interim Review," prepared in August 1977 for the Ship Support Improvement Project of the Naval Sea Systems Command.

TABLE 4-1A
Equipment Logs and Operating Records

EQUIPMENT LOGS AND OPERATING RECORDS	Maintenance Operations	Test Results	Inspection Results	Tasks Completed	Tasks Outstanding	Estimated Time for Tasks	Priorities	Reasons for Deferrals	Logistics Monitoring and Control	Inventory	Historical Demands	Response Time	Parts on Order	Other Outside Assistence Requirements	Configuration Management	Inventory of Equipment Configurations	Alterations Requested	Alterations Outstanding	Priorities	Equipment Performance	Equipment Identification	Operating Time	Stress Information	Failure Occurrences	Downtime	Operating Parameters	Cost	Problem Diagnosis	Description of Problem	Failed Parts	Operating Environment	Analysis of Problem	Readiness	Equipment Conditions	Manpower Conditions	Supply Conditions	Overall Ability to Peform Mission
Weapons Equipment Logs																																					
Smooth Weapons System Log																																					
Non-Expendable SWS Equipment Status Log		●						●			●			●							●[1]	●	●	●	●				●				●[2]				
Sonar Contact Log																						●	●	●	●												
Magazine Temperature Record																															●						
Hull, Mechanical and Electrical (HM&E) Equipment Logs																																					
Engineering Log																															●						
Engineer's Bell Book																															●						
Main Engine Operating Records																						●				●					●						
Fireroom Operating Records																						●				●					●						
Boiler Tube Removal Sheets		●																			●[3]			●													
Boiler Repair Welding Records		●		●[4]																				●													
Feedwater Log																										●											
Boiler Water Treatment Log		●	●																			●		●		●											
Water Jacket Treatment Log																										●					●						
Heat Control Survey Report & Log																																					
Prairie Masker System Log																						●				●											
Diesel Engine Operating Record																						●	●			●											
Electrical Log																						●				●											
Distilling Plant Operating Record																						●				●											
Refrig./Air Cond. Equip. Operating Record																						●				●											
Air Compressor Operating Record																																					
Air Test Log																																					
Interior Comm. Room Operating Recd.																						●															
Gyrocompass Operating Record																						●															
Gyrocompass Service Record		●	●								●										●								●								
Diesel Engine Trend Analysis Record																																					

Notes:
1. 4-Character EIC.
2. Status category code; see Naval Ordnance Instruction (NAVORDINST) 8810.2A.
3. Manufacturer and model.
4. Job Sequence Number (JSN) identified.
5. AN designator, manufacturer.

TABLE 4-1B
INSPECTION AND TEST REPORTS

INSPECTION AND TEST REPORTS	Maintenance Operations	Test Results	Inspection Results	Tasks Completed	Tasks Outstanding	Estimated Time for Tasks	Priorities	Reasons for Deferrals	Logistics Monitoring and Control	Inventory	Historical Demands	Response Time	Parts on Order	Other Outside Assistance Requirements	Configuration Management	Inventory of Equipment Configurations	Alterations Requested	Alterations Outstanding	Priorities	Equipment Performance	Equipment Identification	Operating Time	Stress Information	Failure Occurrences	Downtime	Operating Parameters	Cost	Problem Diagnosis	Description of Problem	Failed Parts	Operating Environment	Analysis of Problem	Readiness	Equipment Conditions	Manpower Conditions	Supply Conditions	Overall Ability to Peform Mission
Weapons Equipment Reports																																					
Fleet Operational Range Accuracy Check Site (FORACS) Report		•																																•	•	•	
Combat Systems Readiness Review (CSRR) Report		•	•		•																													•		•	
Weapon System Review Report			•		•																																
Ordnance Special Assistance Team (OSAT) Report.																																			•		
Weapon System Accuracy Trial Report		•			•																																
Ship Qualification Trial (SQUAT) Report		•			•																													•	•	•	
Conventional Ordnance Inspection Report			•											•																							
Gun Wear/Star Gauge Report			•											•							•[1]																
ASROC Launcher MK. 112 & SVTT MK 32 Inspection Report			•											•							•[1]																
Surface Launched Missile Firing Report		•																			•[2]													•			
Raw Data from Surf. Launched Miss. Test		•																																			
Electromagnetic Interference Report		•																																			
Electronic Countermeasure Test Results		•																																•			
Report of Degaussed Magnetic Condition					•																																
HM&E Equipments Reports																																					
Engineering Trial Reports		•																																•			
Propulsion Examining Board (PEB) Light-Off Examination Report					•																													•	•		
PEB Operating Propulsion Plant Exam. Report					•																													•	•		
Boiler Appraisal			•		•																																
Annual Thin Hull Inspection Report			•											•																							
Underwater Hull Inspection Report			•																																		
Steering System Inspection Report			•		•																																
Insp. Report on Gasoline Tanks, Etc.			•																																		
Weekly PMS Test of Electrical Equipment			•																		•[1]																
Gyrocompass Quarterly Inspection Report			•																																		
Diesel Inspection Report			•																							•			•					•			•

Notes: 1. Mark/mod.
2. Naval Ammunitions Logistics Code (NALC).

TABLE 4-1B (cont'd)

	Maintenance Operations	Test Results	Inspection Results	Tasks Completed	Tasks Outstanding	Estimated Time for Tasks	Priorities	Reasons for Deferrals	Logistics Monitoring and Control	Inventory	Historical Demands	Response Time	Parts on Order	Other Outside Assistance Requirements	Configuration Management	Inventory of Equipment Configurations	Alterations Requested	Alterations Outstanding	Priorities	Equipment Performance	Equipment Identification	Operating Time	Stress Information	Failure Occurrences	Downtime	Operating Parameters	Cost	Problem Diagnosis	Description of Problem	Failed Parts	Operating Environment	Analysis of Problem	Readiness	Equipment Conditions	Manpower Conditions	Supply Conditions	Overall Ability to Perform Mission
Electronics Equipments Reports																																					
Supplementary Radio (SUPRAD) Operational Assessment Report		●																																			
Leak Test of Sealed Sources (Radiac)		●																																			
Reports Applicable to All Equipments																																					
INSURV Report																																					
Post Inspection and Survey (INSURV) Inspection Report																																	●				

TABLE 4-1C
SUMMARY MAINTENANCE CONDITION AND READINESS REPORTS

SUMMARY MAINTENANCE CONDITION AND READINESS REPORTS	Maintenance Operations	Test Results	Inspection Results	Tasks Completed	Tasks Outstanding	Estimated Time for Tasks	Priorities	Reasons for Deferrals	Logistics Monitoring and Control	Inventory	Historical Demands	Response Time	Parts on Order	Other Outside Assistance Requirements	Configuration Management	Inventory of Equipment Configurations	Alterations Requested	Alterations Outstanding	Priorities	Equipment Performance	Equipment Identification	Operating Time	Stress Information	Failure Occurrences	Downtime	Operating Parameters	Cost	Problem Diagnosis	Description of Problem	Failed Parts	Operating Environment	Analysis of Problem	Readiness	Equipment Conditions	Manpower Conditions	Supply Conditions	Overall Ability to Peform Mission
Report of Significant Casualties (CASREPT)				•[1]		•		•					•	•							•[2]			•					•	•[3]		•		•			•[4]
Force Status Reporting System (FORSTAT)																																		•	•	•	•
Commanding Officer's Narrative Reports (COMNAR) on SNS																													•			•		•	•	•	
Department 8 o'clock Report				•				•																										•			•[4]

Notes:
1. Job Sequence Number (JSN) identified.
2. 4-character Equipment Identification Code (EIC).
3. Allowance Parts List (APL) or Component Identification (CID) number.
4. CASREPT readiness rating code (c-rating); see Naval Warfare Publication (NWP 7), Table 4-1.

TABLE 4-1D
SAFETY HAZARD REPORTS

SAFETY HAZARD REPORTS	Maintenance Operations	Test Results	Inspection Results	Tasks Completed	Tasks Outstanding	Estimated Time for Tasks	Priorities	Reasons for Deferrals	Logistics Monitoring and Control	Inventory	Historical Demands	Response Time	Parts on Order	Other Outside Assistance Requirements	Configuration Management	Inventory of Equipment Configurations	Alterations Requested	Alterations Outstanding	Priorities	Equipment Performance	Equipment Identification	Operating Time	Stress Information	Failure Occurrences	Downtime	Operating Parameters	Cost	Problem Diagnosis	Description of Problem	Failed Parts	Operating Environment	Analysis of Problem	Readiness	Equipment Conditions	Manpower Conditions	Supply Conditions	Overall Ability to Perform Mission
Serious Safety Deficiency Report					●[1]																			●					●					●[2]			
Forces Afloat Accident/Near Accidental Report																								●					●								

NOTES: 1. JSN identified.
2. Safety designation code; see COMMAVSURFLANTINT 9000.1, article 5100.2

4. Accessibility of Data Sources

The central location of MDS data, from which most maintenance data can be accessed, is the Navy Maintenance Support Office (NAMSO) in Mechanicsburg, Pennsylvania. NAMSO maintains the Central Data Bank and prepared reports based on this data. The accessible data consists, in the main, of material from OPNAV 4790/2 series, NAVSUP 1250, DD 1348, and some INSURV and Safety Reports recorded on 4790 forms.

Non-MDS sources are generally manual and are not held in a central location. They may be accessed from individual ships, shipyards, and test and evaluation offices. Since there is no central location for all these data, accessibility will present a logistics problem that will require sampling procedures.

The Casualty Reports (CASREPS), from which the data of critical equipment failures and the effect of these failures on the capabilities of the reporting Navy ship may be assessed, can be obtained from Navy Ships Parts Control Center (SPCC), Mechanicsburg, PA. The CASREP reports can be used to assist in identifying problem equipments, support deficiencies, and maintenance difficulties, etc.

5. Summary

A large volume of maintenance data currently exists and is continuously being collected by the U.S. Navy. It is divided into two general categories: (1) MDS data that is available in a computerized version from a central location; (2) Non-MDS data that is available in manual format and must be accessed from individual ships and maintenance facilities.

Most of the maintenance information available is not fully useful to this program. That maintenance information that is likely to be useful is: (1) maintenance jobs and tasks; (2) equipment to which jobs and tasks apply; (3) real-time man hours, and troubleshooting time required for each maintenance job; (4) priority of each management job; and (5) rating of personnel scheduled for each type of maintenance job. There may be data on maintainability problems for pieces of equipment and/or maintenance jobs, but this is uncertain. If there are such data, it will probably be spotty and incomplete, at best.

APPENDIX F

SOURCES OF OPERATOR WORKLOAD

Appendix F

Sources of Operator Workload

It is generally agreed that there are six clearly identifiable reasons for unmanageable operator/maintainer workload. These are:

- Perceptual saturation
- Need to perform tasks concurrently
- Timeline compression
- Operator physiological limitations
- Excessive small scale, routine operations
- Operator cognitive time-bandwidth barriers
- Indiscriminate automation

Each of these problems is discussed in the following paragraphs.

Perceptual Saturation

This phenomenon manifests itself when a number of critical events occur simultaneously, with the result that the operator is unable to cope with the situation. For example, when several events have occurred and all demand perceptual attention in casualty control, the serial processing operator easily loses track of the threats and control over his reactions.

Concurrent Task Performance

Operators frequently must perform several tasks concurrently such as maintaining visual awareness out of the control room while monitoring critical displays with the control/monitor instruments. Combined with these visual tasks may be the simultaneous need for voice contact and communication with the maintenance team. This situation causes conflicting demands on his sensors and supporting control processing resources.

Timeline Compression

Since casualty control procedures are highly time-stressed, there is very little time available to the operator to exercise judgement and take action. In a typical encounter of a major main reduction gear lube oil leak, the operator has a whole host of tasks to complete from detection/confirmation of the event, location of the causes, system status, and appropriate procedures/actions. If for mission phase, plant status or other reasons the time available is very short, the same number of tasks still must be performed but in a much compressed time-scale.

Operator Physiological Limits

Humans are limited in the rate at which they can perform manual tasks. This characteristic is referred to here as operator motor limits even though portions of this limit have been identified as cognitive. An operator typically needs on the order of one-half second to make a simple control adjustment. Consequently, he is incapable of manual execution requiring much more than two manually executed corrections per second. Where this situation occurs, some form of enhancement or partial automation is not just desirable but mandatory.

Excessive Small Scale Tasks

Operations requiring several small steps can significantly increase operator workload. Such tasks are typically time-consuming. In performing these tasks, operators are prone to making errors of omission, i.e., skipping steps. In addition, such tasks impose a formidable memory burden on operators that can adversely impact performance on other tasks.

Operator Cognitive Time-Bandwidth Limits

Humans have a finite and relatively small limit on the number of different symbols that can be retained and correlated in primary memory. In the casualty/contingency handling tasks, recognizing particular casualty generally requires consideration of a number of different but related symptoms or factors. Two items can cause overload. First, if the number of factors needed for consideration in the recognition or multiple-source casualty exceeds the humans limit, the diagnosis may be flawed. Second, if the time available to recall or formulate handling procedures is less than the human's ability to formulate a single set, the entire process breaks down - usually catastrophically.

Indiscriminate Automation

Automation can be a mixed blessing. If introduced without proper prior analysis of tasks it can produce the opposite effect, i.e., increase rather than decrease operator workload. In fact, there are at least seven alternatives to automation that can enhance the combined performance of operator and system. These are: (1) improving human engineering in cockpit design, (2) improving procedures, (3) training operators, (4) selecting operators, (5) changing crew composition, (6) improving motivation, (7) prescribing methods to cope with stress.

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